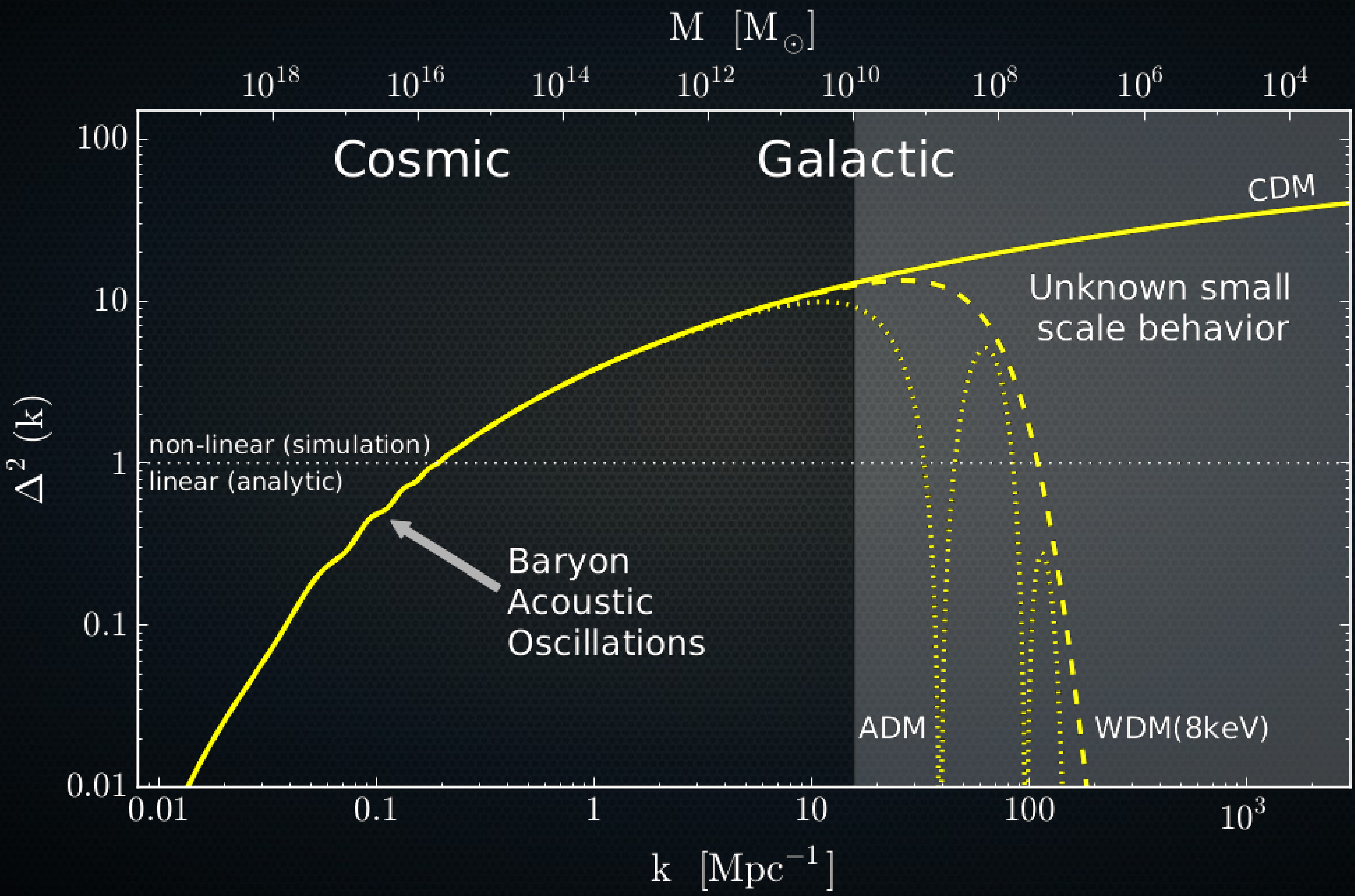
Most Matter is Dark Matter, but that's not all that matters.

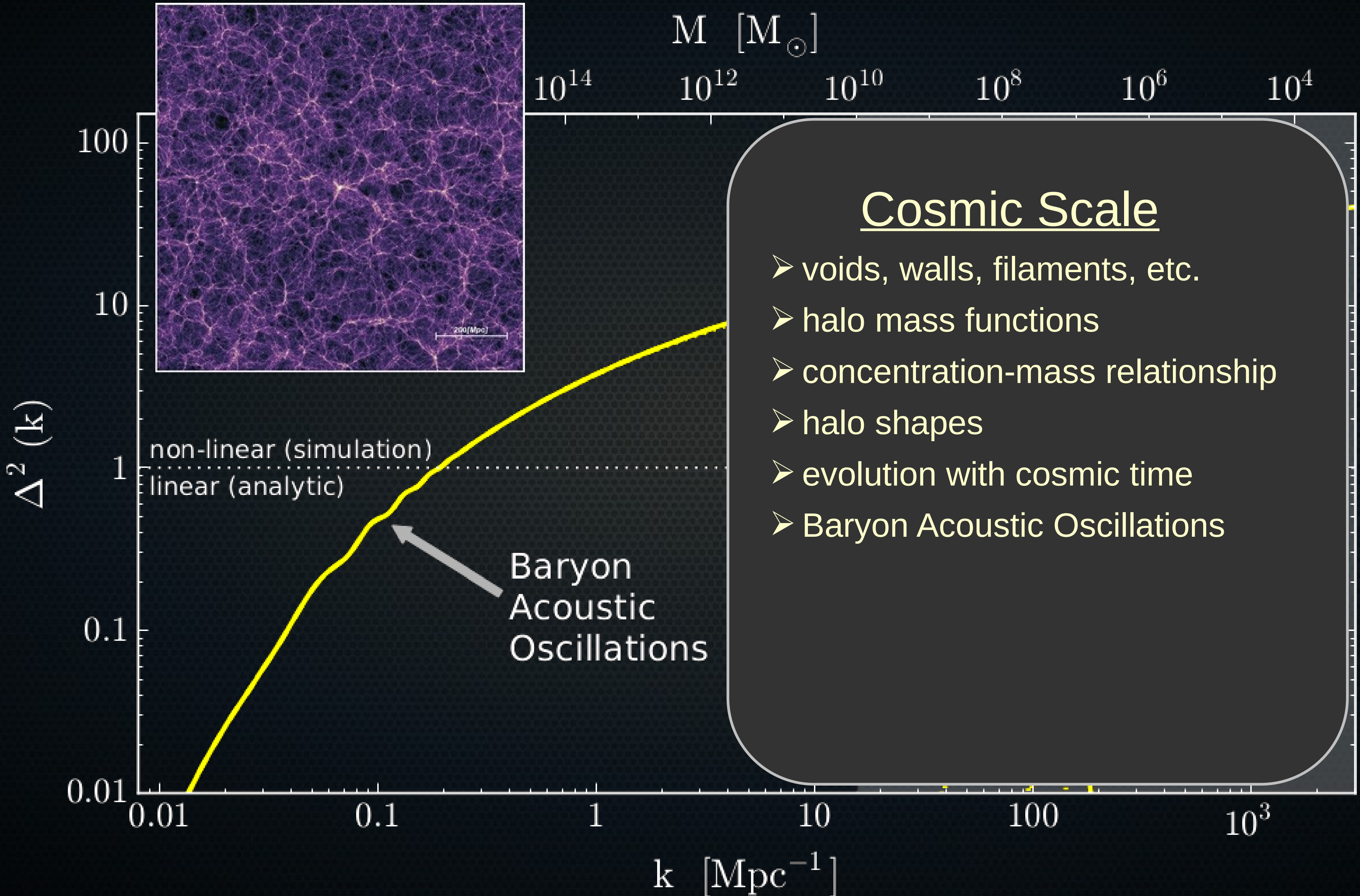
Michael Kuhlen, Berkeley

With J. Diemand (Zurich), J. Guedes (Zurich), M. Lisanti (Princeton), P. Madau (UC Santa Cruz), L. Mayer (Zurich), A. Pillepich (UC Santa Cruz), N. Weiner (NYU), A. Brooks (U. Wisconsin), A. Zolotov (Hebrew U. Jerusalem)

The Domain of Dark Matter Simulations



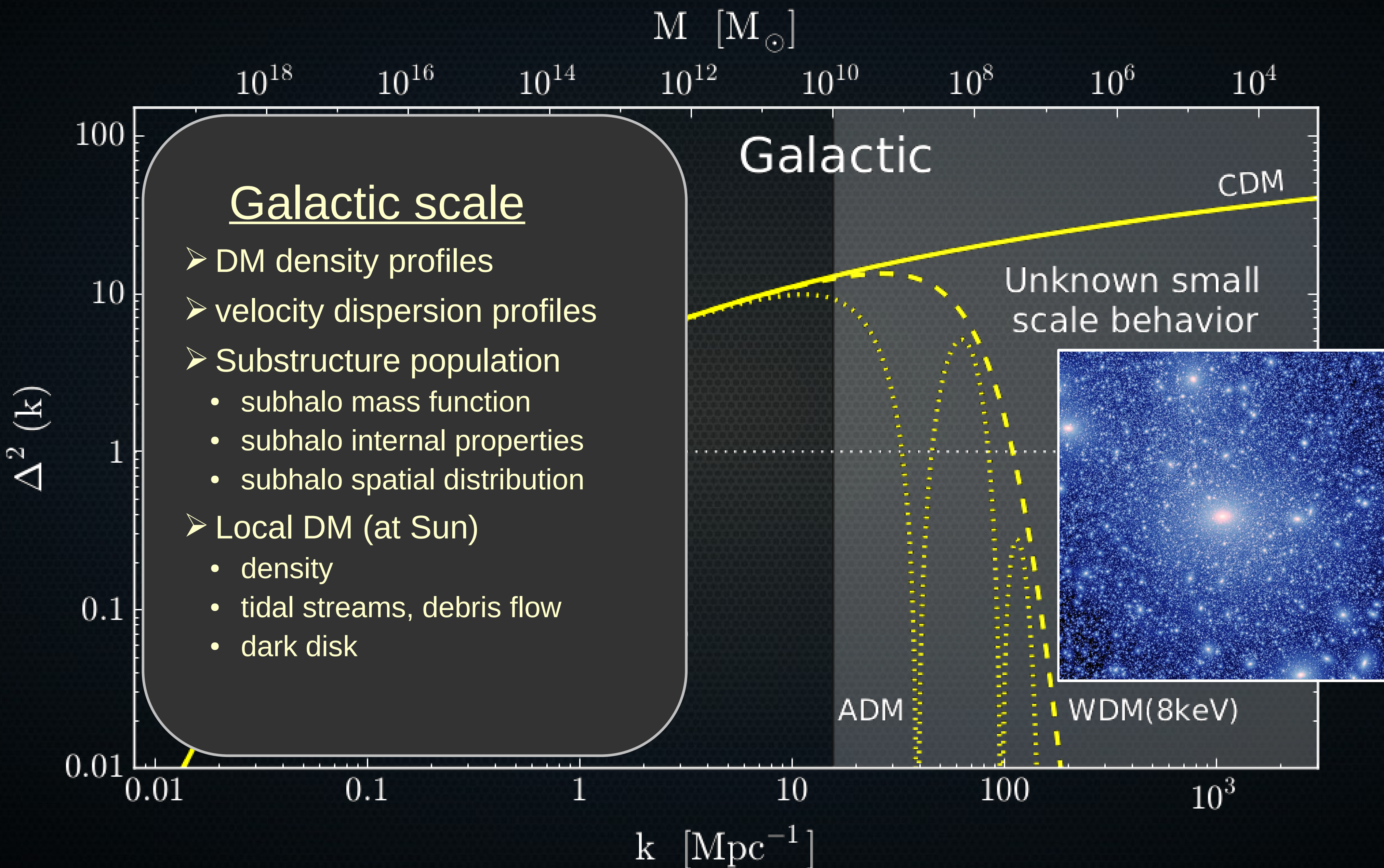
The Domain of Dark Matter Simulations



Cosmic Scale

- voids, walls, filaments, etc.
- halo mass functions
- concentration-mass relationship
- halo shapes
- evolution with cosmic time
- Baryon Acoustic Oscillations

The Domain of Dark Matter Simulations



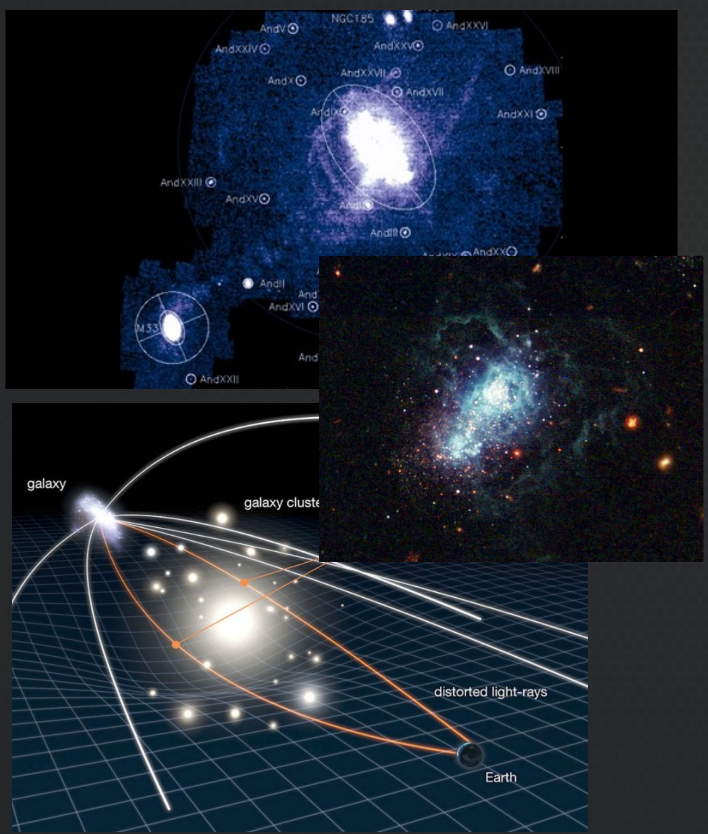
Galactic scale

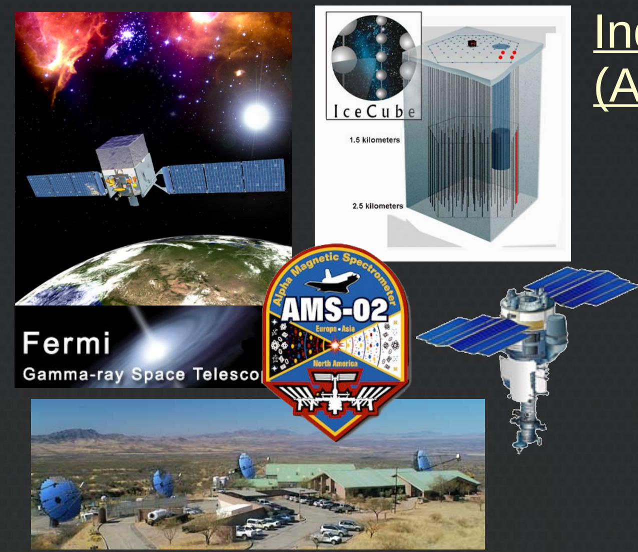
- DM density profiles
- velocity dispersion profiles
- Substructure population
  - subhalo mass function
  - subhalo internal properties
  - subhalo spatial distribution
- Local DM (at Sun)
  - density
  - tidal streams, debris flow
  - dark disk

Dark Matter Detection Applications

Astro-physical Probes

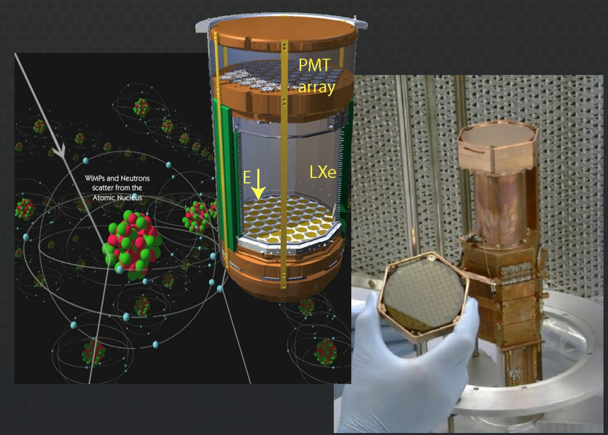
- Dwarf galaxy census
- Stellar kinematics
- Stellar streams
- Gravitational lensing





Indirect Detection (Annihilation)

- Extra-galactic DGRB
- Galactic DGRB
- Clusters
- Galactic Center
- Milky Way Dwarfs
- Dark Subhalos
- e+/e- from local annihilation
- Neutrinos from Earth & Sun
- “Boost factor”



Direct Detection (Nuclear Recoils)

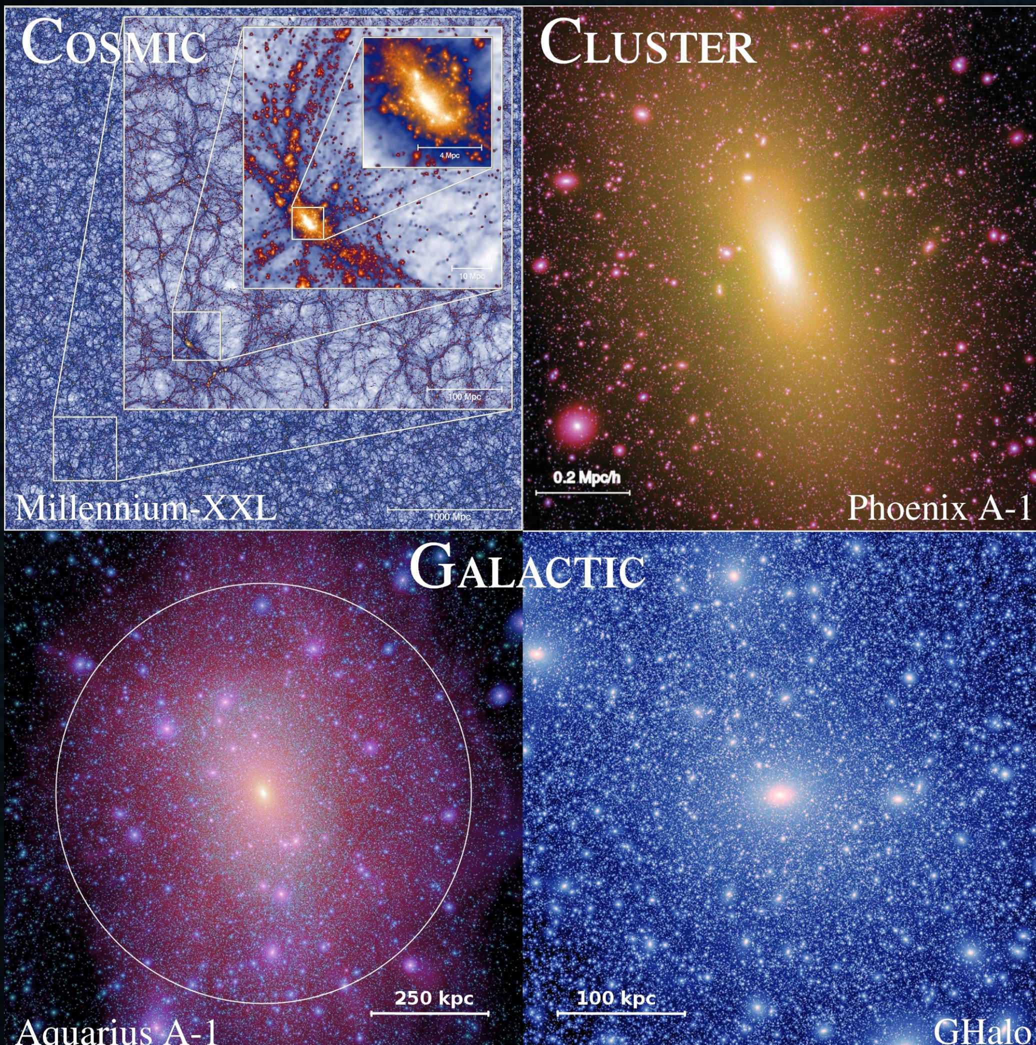
- standard case: “vanilla” WIMPs
- low mass DM, inelastic DM, etc.
- directionally sensitive experiments

The Domain of Dark Matter Simulations

From Kuhlen, Vogelsberger & Angulo 2012 (arXiv:1209.5745)

		LSS		Halos				Substructure						Local		
		voids, walls, filaments	halo mass functions	concentration-mass relation	halo shapes	density profiles	pseudo-phase-space density	mass (or V_{max}) functions	density profiles	central density	spatial distribution	streams	folds & caustics	local density	tidal streams	dark disk
Astrophysical	Dwarf galaxy abundance				■	■		■	■	■	■				■	■
	Dwarf galaxy kinematics							■	■	■						
	Stellar streams				■	■		■			■	■				
	Gravitational lensing	■	■	■	■	■		■	■		■					
Indirect Detection	Extra-galactic DGRB	■	■	■		■		■	■							
	Galactic DGRB				■	■		■	■		■					
	Clusters			■	■	■		■	■							
	Galactic Center					■										
	Milky Way Dwarfs			■		■			■	■						
	Dark Subhalos			■		■		■	■	■	■					
	Local anti-matter													■		
	Neutrinos from Earth & Sun													■	■	■
	Substructure boost							■	■		■		■			
	Sommerfeld boost						■					■	■		■	■
Direct	"Vanilla" ~ 100 GeV DM													■		
	light / inelastic DM													■	■	■
	axions												■	■	■	■
	directionally sensitive experiments													■	■	■

Current State Of The Art



DM-only simulations

Cosmic

Name	Code	L_{box} $[h^{-1}\mathrm{Mpc}]$	N_p $[10^9]$	m_p $[h^{-1}\,M_\odot]$	ϵ_{soft} $[h^{-1}\mathrm{kpc}]$	$N_{halo}^{>100p}$ $[10^6]$
DEUS FUR	Ramses-Deus	21000	550	1.2×10^{12}	$40.0^\dagger$	145
Horizon Run 3	GotPM	10815	370	2.5×10^{11}	150.0	~190
Millennium-XXL	Gadget-3	3000	300	6.2×10^{9}	10.0	170
Horizon-4Π	Ramses	2000	69	7.8×10^{9}	$7.6^\dagger$	~40
Millennium-II	Gadget-3	100	10	6.9×10^{6}	1.0	2.3
MultiDark Run1	Art	1000	8.6	8.7×10^{9}	$7.6^\dagger$	3.3
Bolshoi	Art	250	8.6	1.4×10^{8}	$1.0^\dagger$	2.4

† For AMR simulations (Ramses, Art) ϵ_{soft} refers to the highest resolution cell width.

Cluster

Name	Code	L_{hires} $[h^{-1}\mathrm{Mpc}]$	$N_{p,hires}$ $[10^9]$	$m_{p,hires}$ $[h^{-1}\,M_\odot]$	ϵ_{soft} $[h^{-1}\mathrm{kpc}]$	$N_{sub}^{>100p}$ $[10^3]$
Phoenix A-1	Gadget-3	41.2	4.1	6.4×10^{5}	0.15	60

Galactic

Name	Code	L_{hires} [Mpc]	$N_{p,hires}$ $[10^9]$	$m_{p,hires}$ $[M_\odot]$	ϵ_{soft} [pc]	$N_{sub}^{>100p}$ $[10^3]$
Aquarius A-1	Gadget-3	5.9	4.3×10^{9}	1.7×10^{3}	20.5	82
GHalo	PKDGRAV2	3.89	2.1×10^{9}	1.0×10^{3}	61.0	43
Via Lactea II	PKDGRAV2	4.86	1.0×10^{9}	4.1×10^{3}	40.0	13

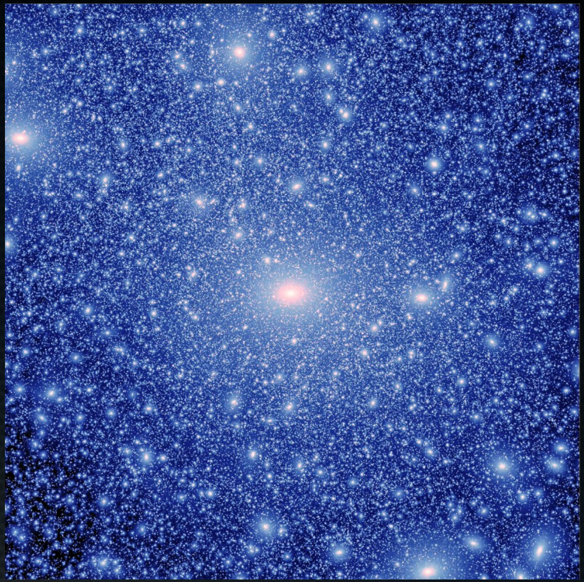
Kuhlen, Vogelsberger & Angulo 2012 (arXiv:1209.5745)

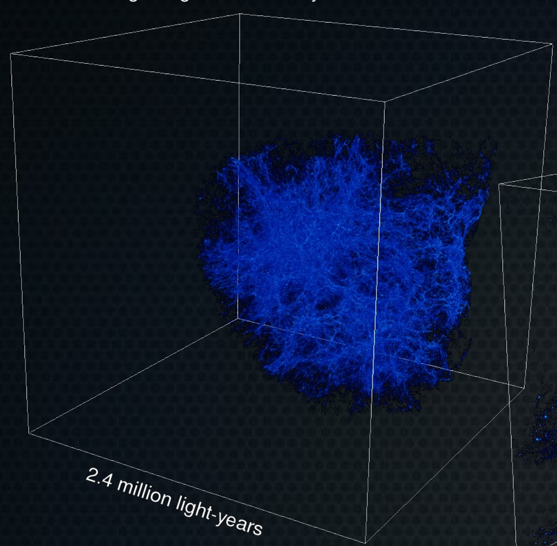
The Via Lactea Project

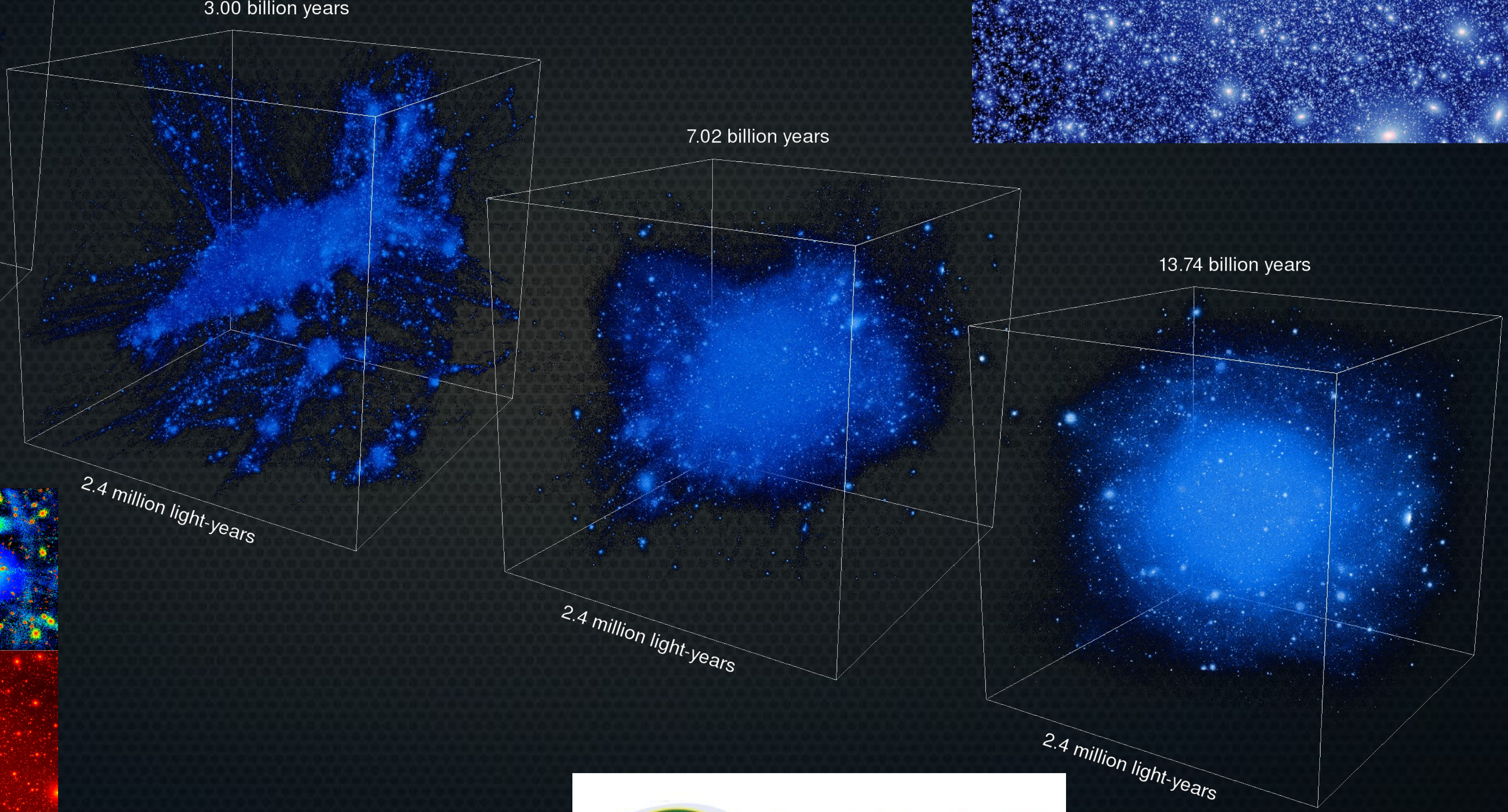
J. Diemand – M. Kuhlen – P. Madau

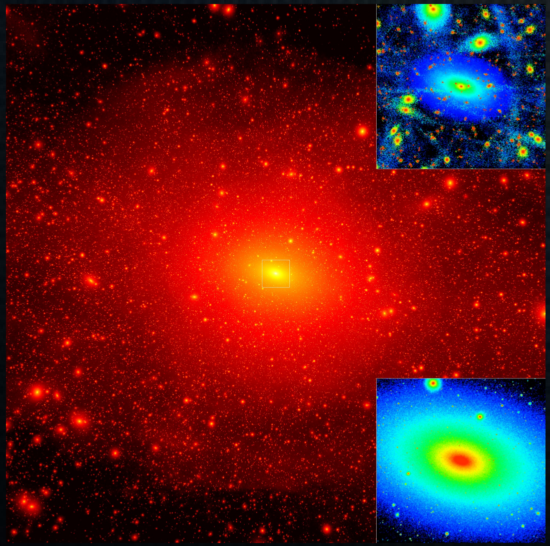
(& B. Moore, D. Potter, J. Stadel, M. Zemp)

GHALO
Stadel et al. (2009)
2.1 billion particles, 1,000 $M_\odot$









VIA LACTEA II
Diemand, Kuhlen et al. 2008
1.1 billion particles, 4,000 $M_\odot$

SciDAC Scientific Discovery through Advanced Computing

Office of Science INCITE Advancing America's Science and Industrial Competitiveness

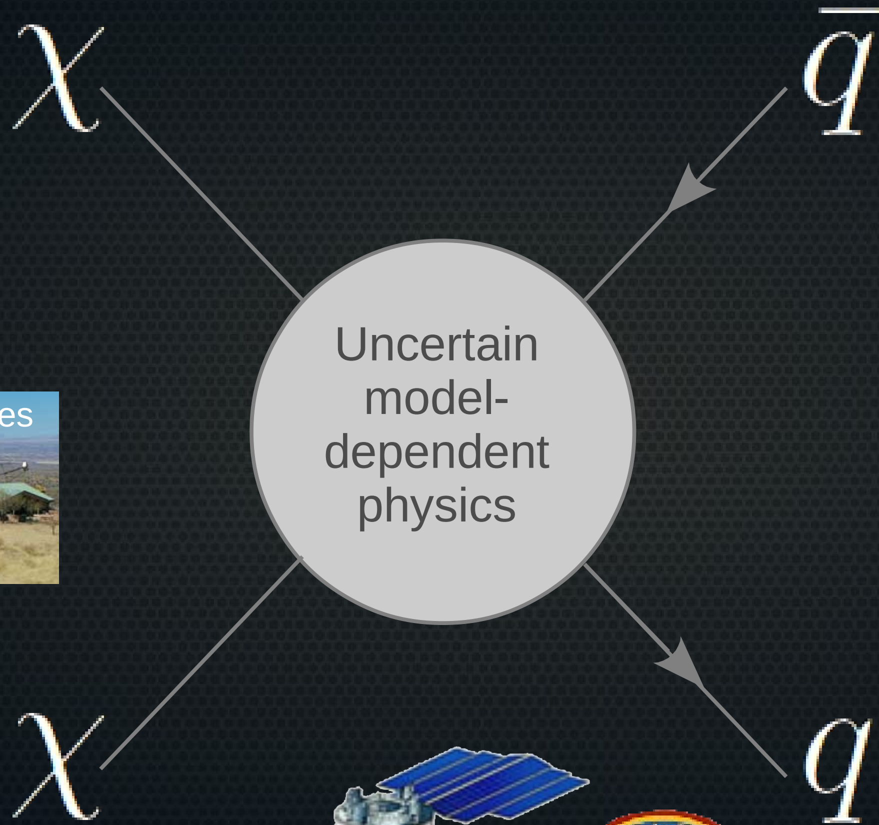
The Via Lactea Project

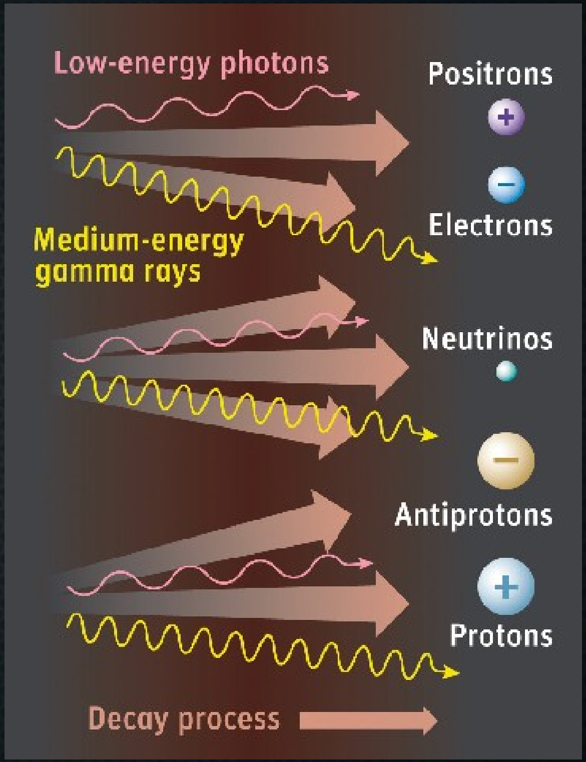
J. Diemand – M. Kuhlen – P. Madau
(& B. Moore, D. Potter, J. Stadel, M. Zemp)

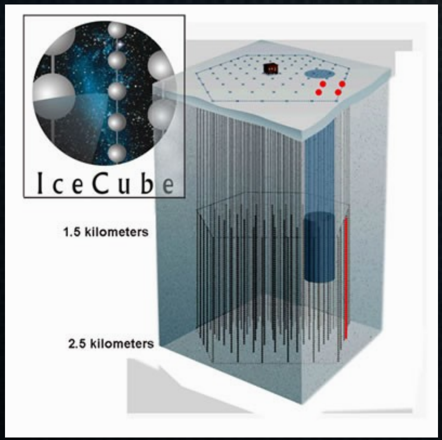
VIA LACTEA II (1.1 billion particles, 4,000 $M_{\odot}$)

Indirect Detection of Dark Matter

Annihilation sets the abundance of dark matter in the early universe.
Possibly detectable signal from DM concentrations in the present.

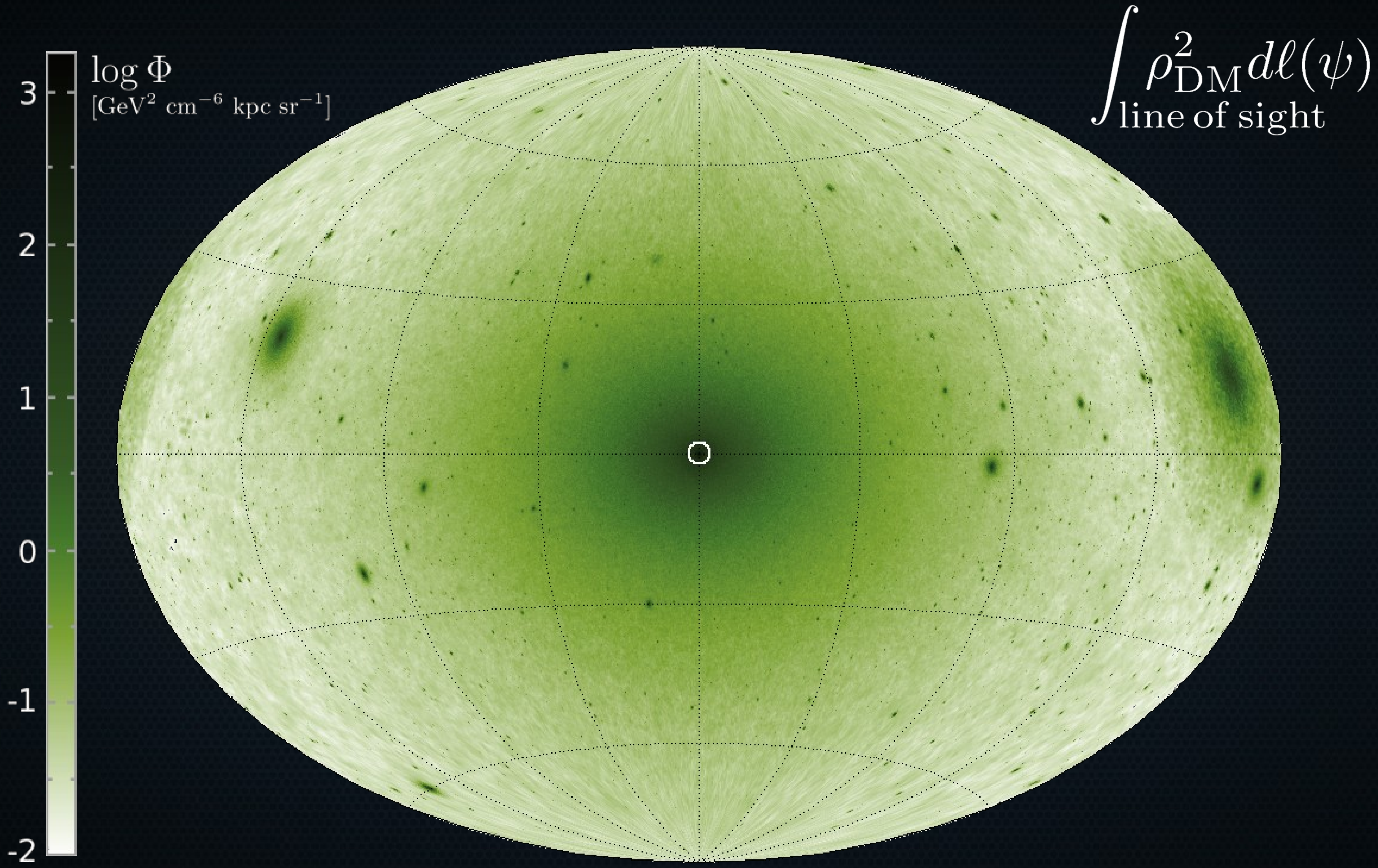






PAMELA satellite

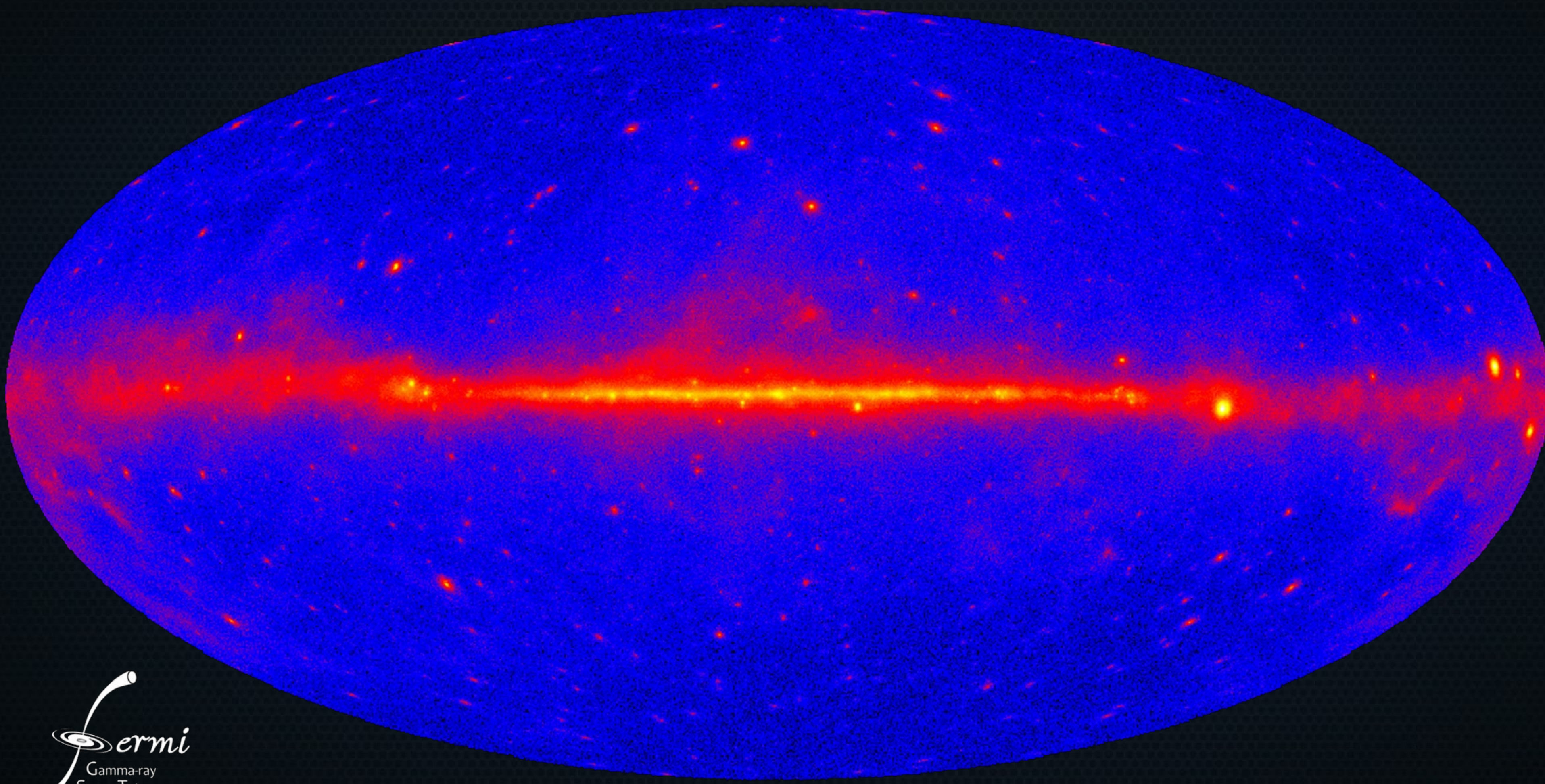
Indirect Detection of Dark Matter



Kuhlen, Diemand, & Madau (2008)

Indirect Detection of Dark Matter

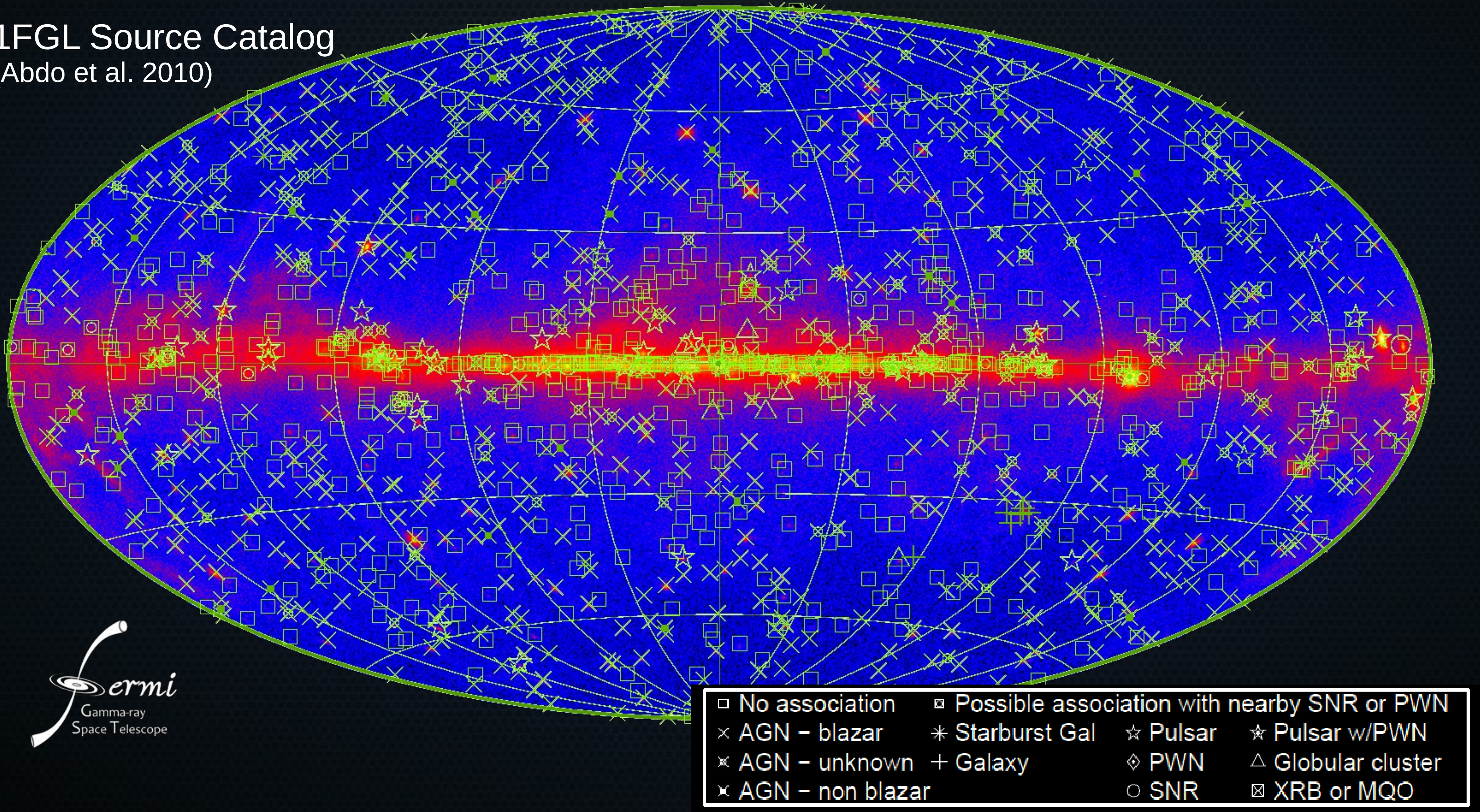
The Fermi Gamma-ray Space Telescope was launched on June 11th 2008 and has been observing the sky for more than 4 years.



Indirect Detection of Dark Matter

So far, no dark matter signal has been detected. ☹   Stay tuned...

1FGL Source Catalog
(Abdo et al. 2010)



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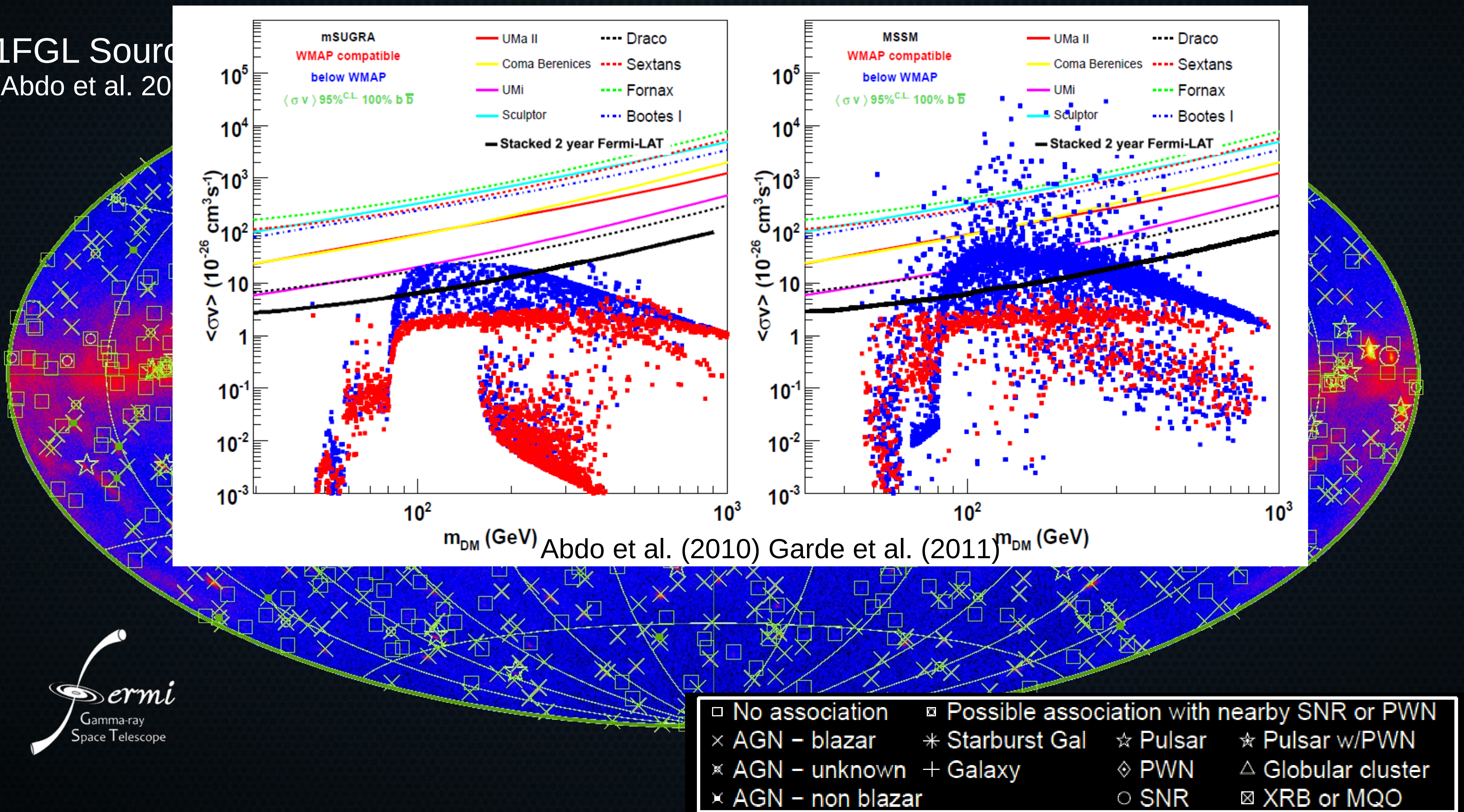
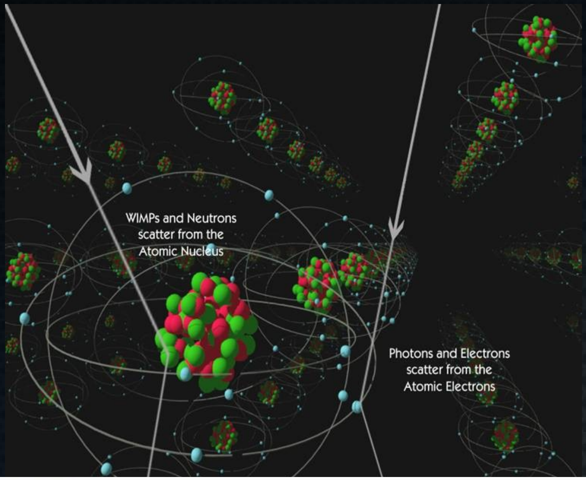
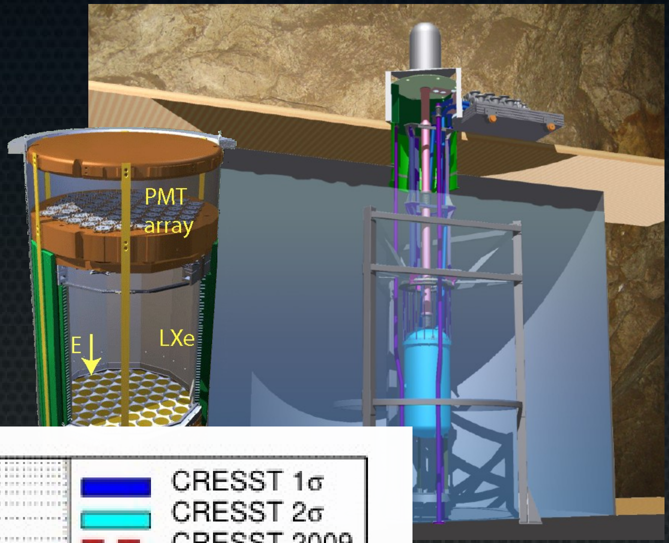
1FGL Sourc
(Abdo et al. 20

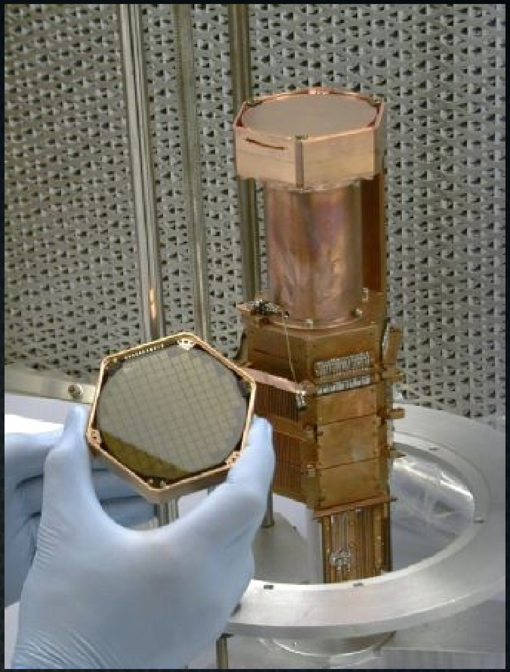


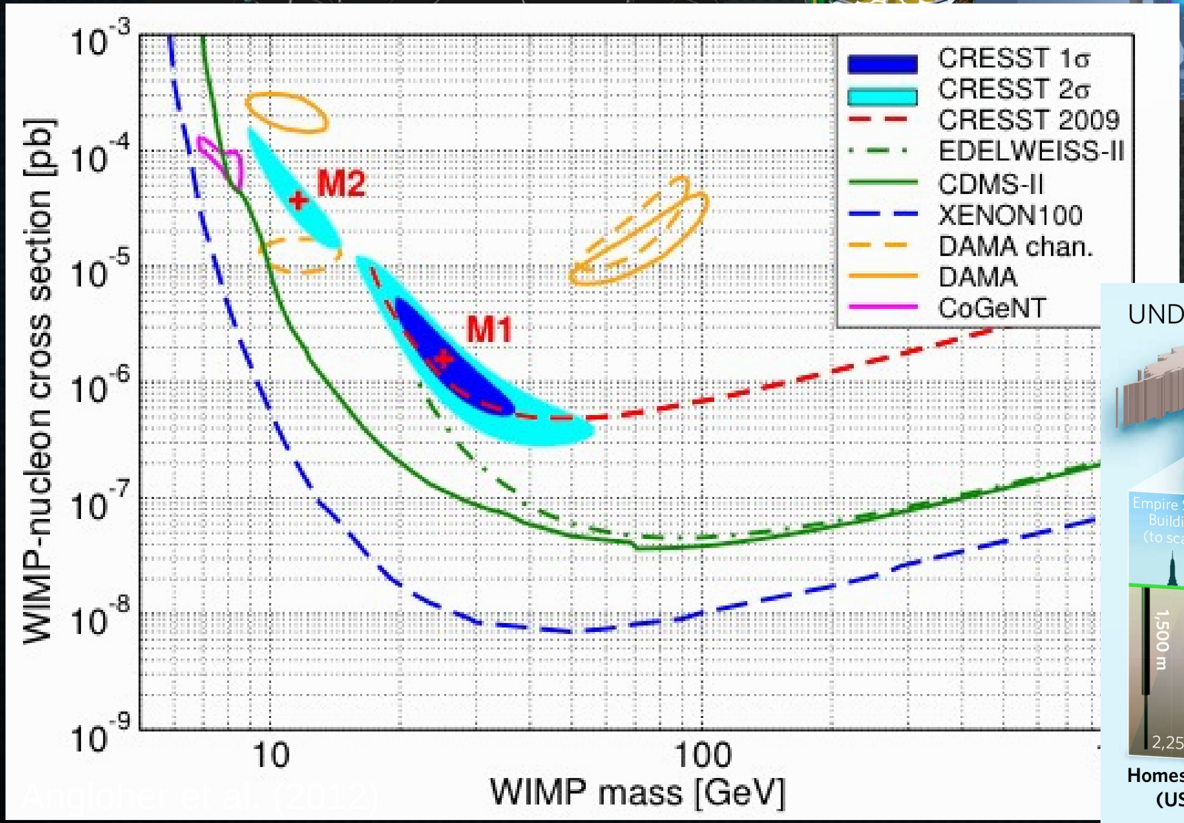
Abdo et al. (2010) Garde et al. (2011)

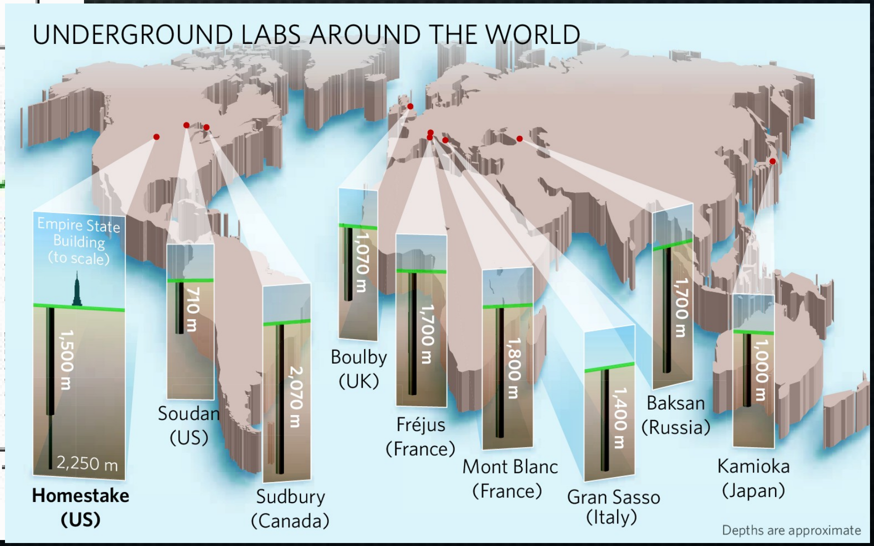
Direct Detection of Dark Matter





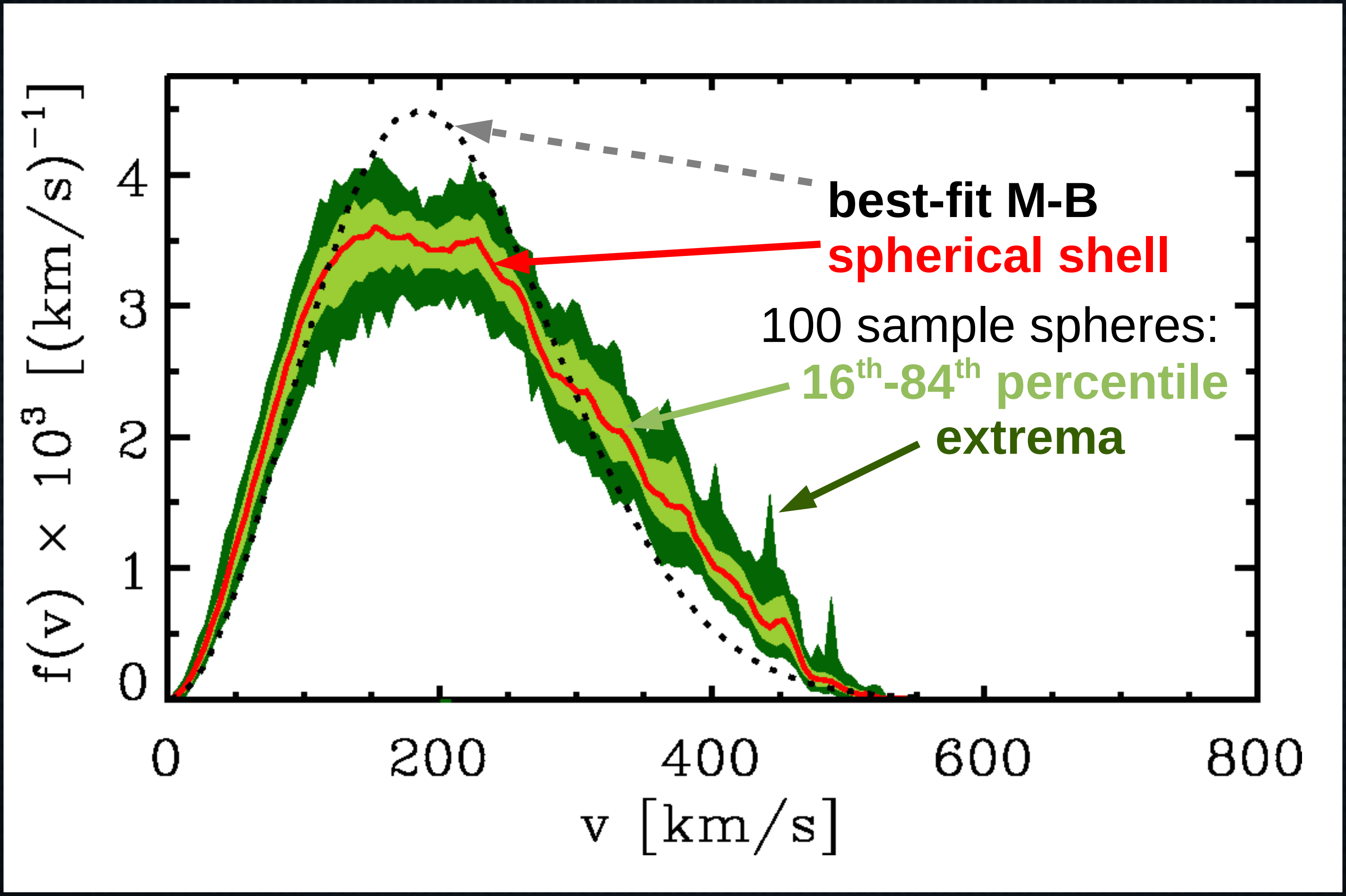






I. Velocity Substructure and Direct Detection

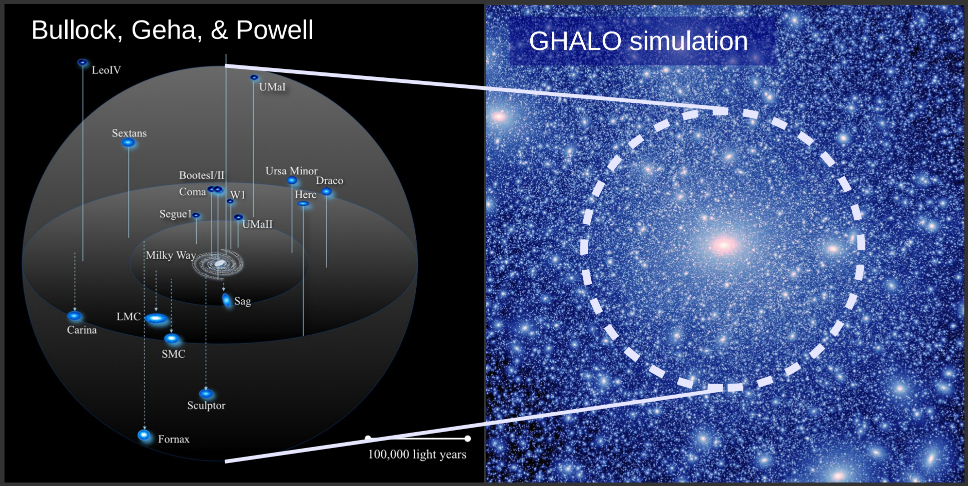
$$\frac{dR}{dE_R} = N_T M_N \frac{\rho_\chi \sigma_n}{2m_\chi \mu_{ne}^2} \frac{(f_p Z + f_n(A-Z))^2}{f_n^2} F^2[E_R] \boxed{\int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv}$$



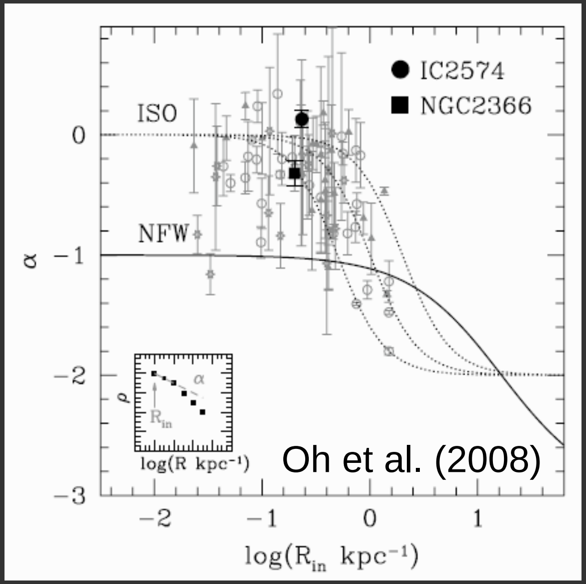
Kuhlen et al. (2010); see also Hansen et al. (2005), Vogelsberger et al. (2009)

Small Scale Challenges for CDM

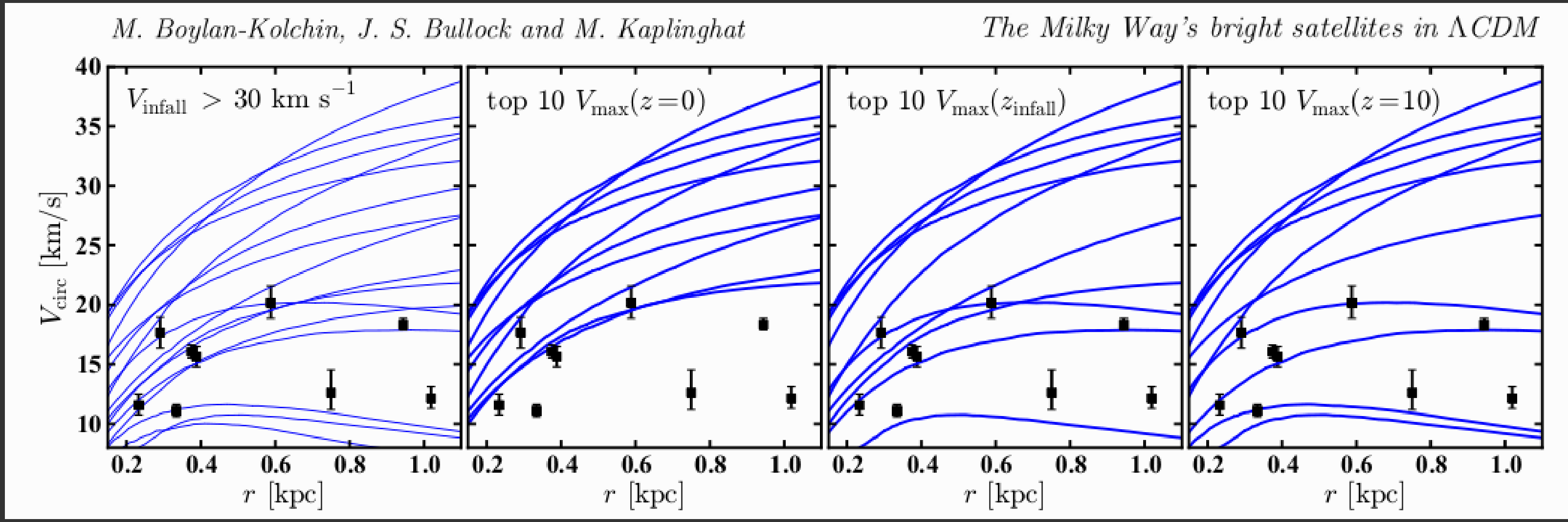
Missing Satellites Problem



Cusp/Core Problem



Too Big To Fail Problem



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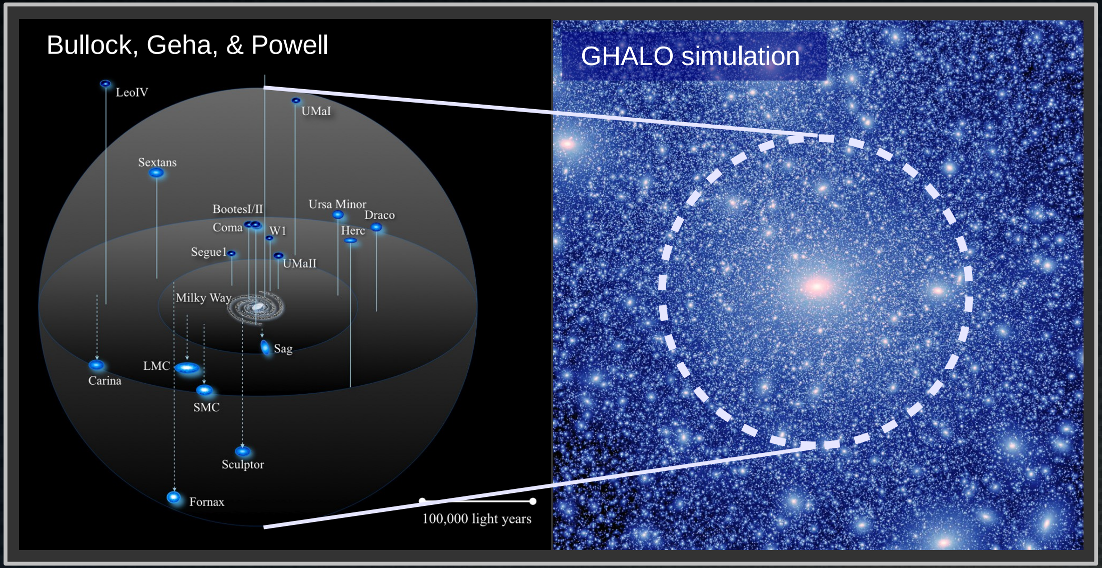
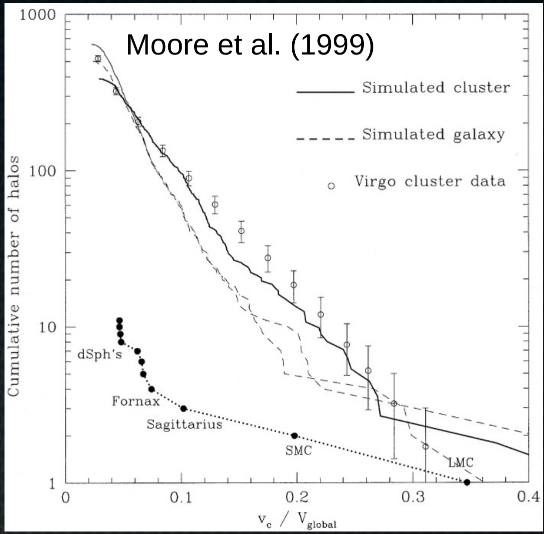
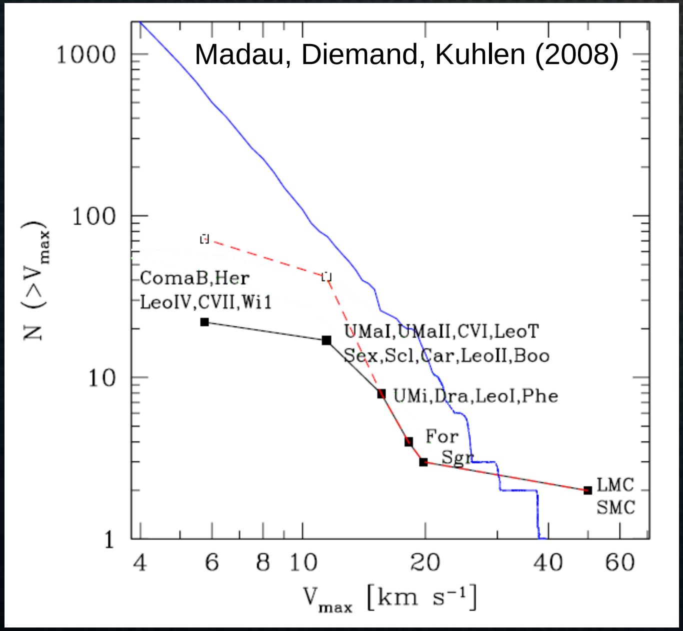
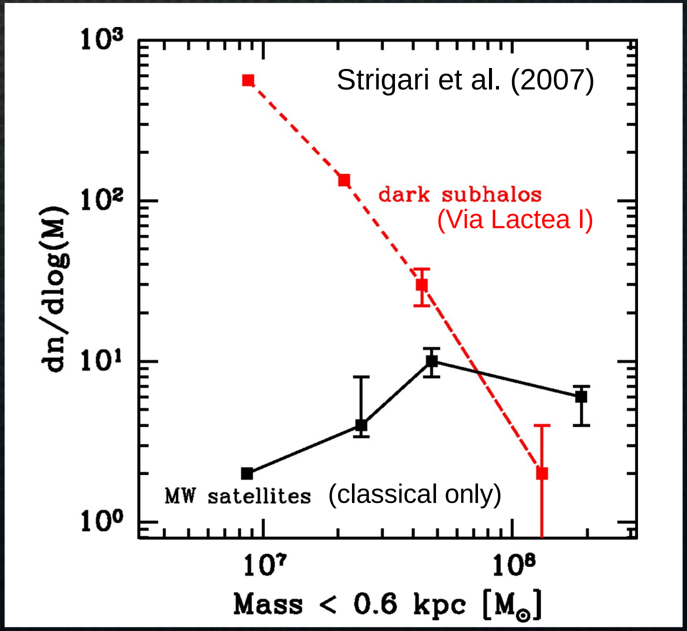






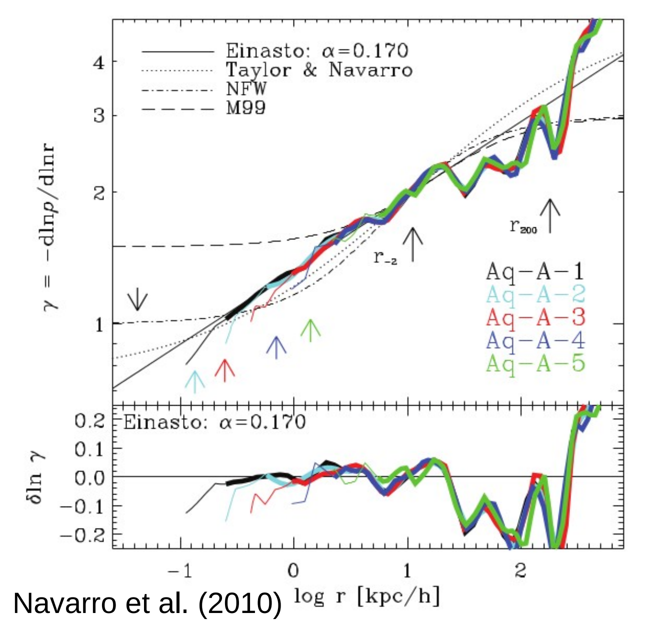


Cusp/Core Problem

DM-only N-body simulations predict cuspy density profiles: $\gamma \equiv -\frac{d\ln\rho}{d\ln r} \lesssim 1$

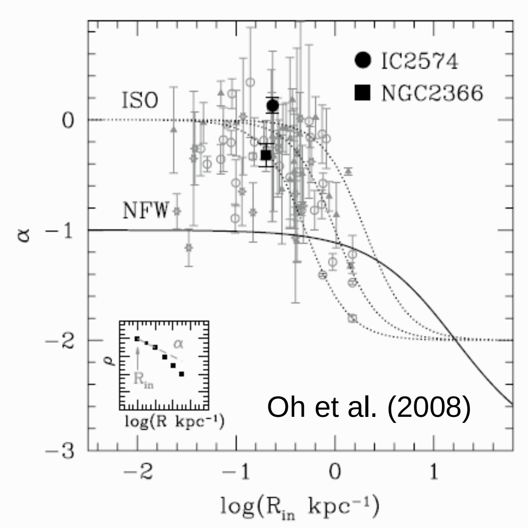
$$\rho(r) = \frac{\rho_s}{(r/r_s)(r/r_s+1)^2} \quad \text{(NFW)}$$

$$\ln\frac{\rho(r)}{\rho_s} = -\frac{2}{\alpha}\left[(r/r_s)^\alpha - 1\right] \quad \text{(Einasto)}$$

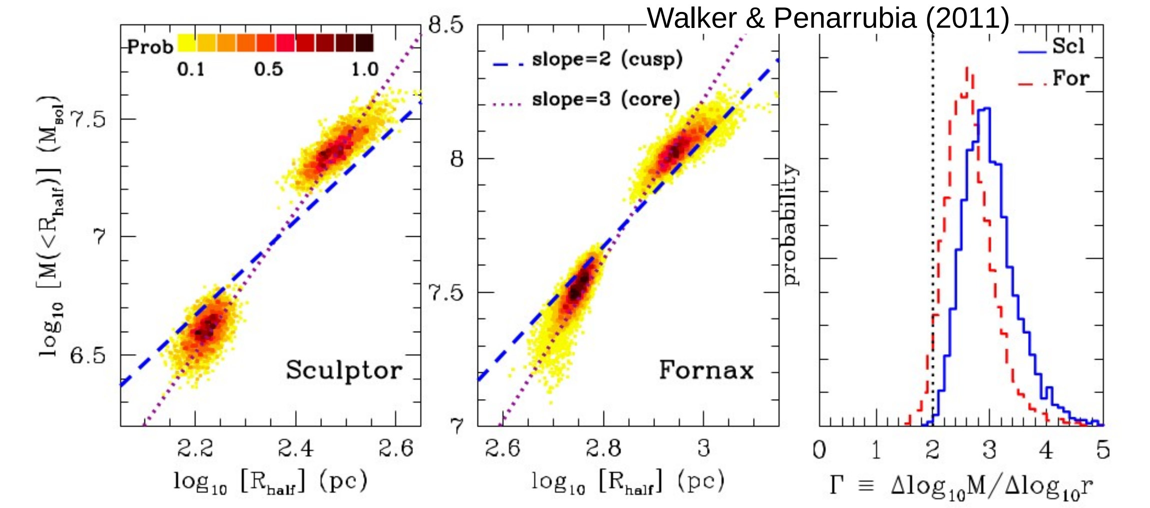


Navarro et al. (2010)

Observations in dwarf galaxies appear to prefer cores: $\gamma \equiv -\frac{d\ln\rho}{d\ln r} \approx 0$

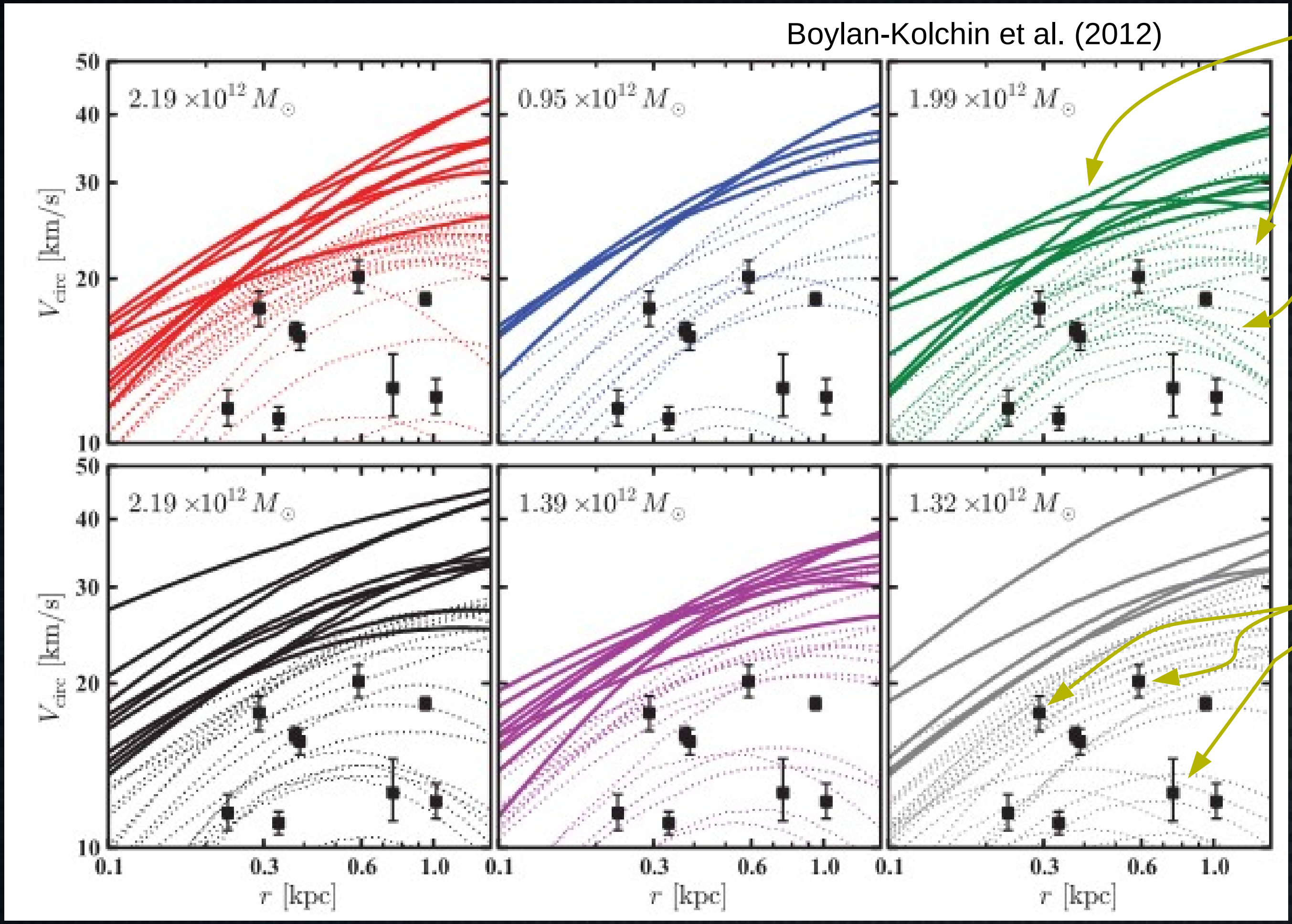


Oh et al. (2008)



Walker & Penarrubia (2011)

„Too Big To Fail“



Circular velocity curves for subhalos in the six Aquarius host halos.

$$V_{\rm circ}(r) = \sqrt{\frac{G\,M(<r)}{r}}$$

The circular velocity at the half-light radius of the Milky Way's classical dwarf satellite galaxies determined from radial velocities of ~100's of stars each. (Wolf et al. 2010)

The DM-only simulations always contain a population of subhalos that are **too dense** or **too massive** to host any of the dwarf spheroidals with well constrained $V_c(r_{1/2})$.

Beyond Cold & Collisionless DM-only Simulations

Cold and Collisionless DM-only Simulations
[Millennium II, Via Lactea II, Aquarius, etc.]

Alternative Dark Matter Physics

Warm Dark Matter
Self-Interacting Dark Matter
???

Include Baryonic Physics

Gas Cooling
Star Formation
Feedback

Beyond Cold & Collisionless DM-only Simulations

Cold and Collisionless DM-only Simulations
[Millennium II, Via Lactea II, Aquarius, etc.]

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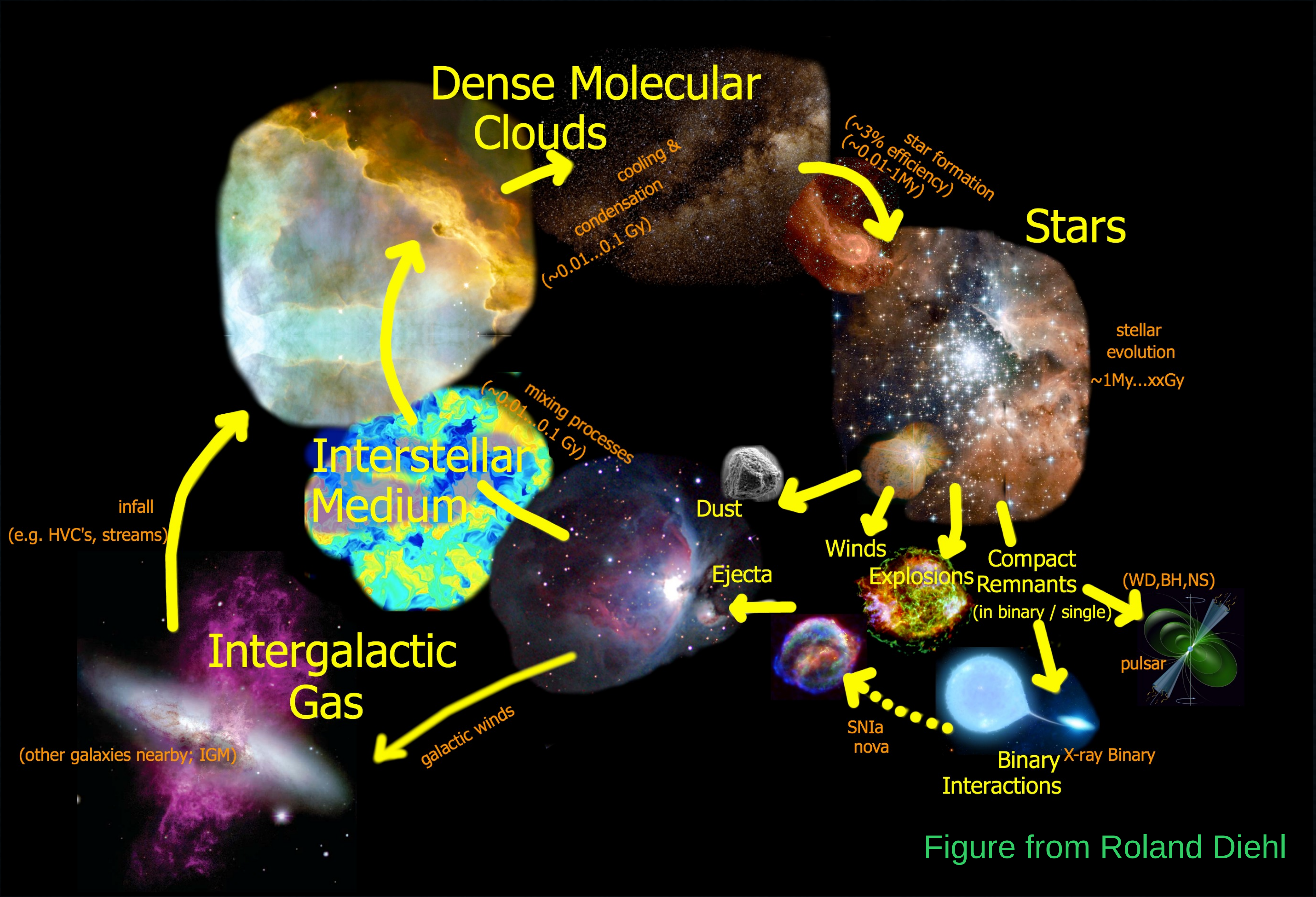
Beyond DM-only: including baryonic physics

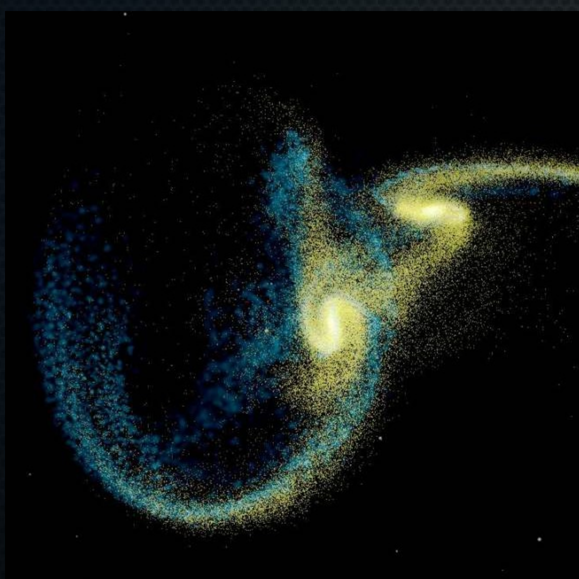


Treatment of Hydrodynamics

$$\frac{\partial \boldsymbol{u}}{\partial t} + \frac{\partial \boldsymbol{f}}{\partial x} = 0 \qquad \boldsymbol{u} = \begin{pmatrix} \rho \\ \rho v \\ \rho E \end{pmatrix} \qquad \boldsymbol{f} = \begin{pmatrix} \rho v \\ \rho v^2 \\ (\rho E + p) v \end{pmatrix}$$

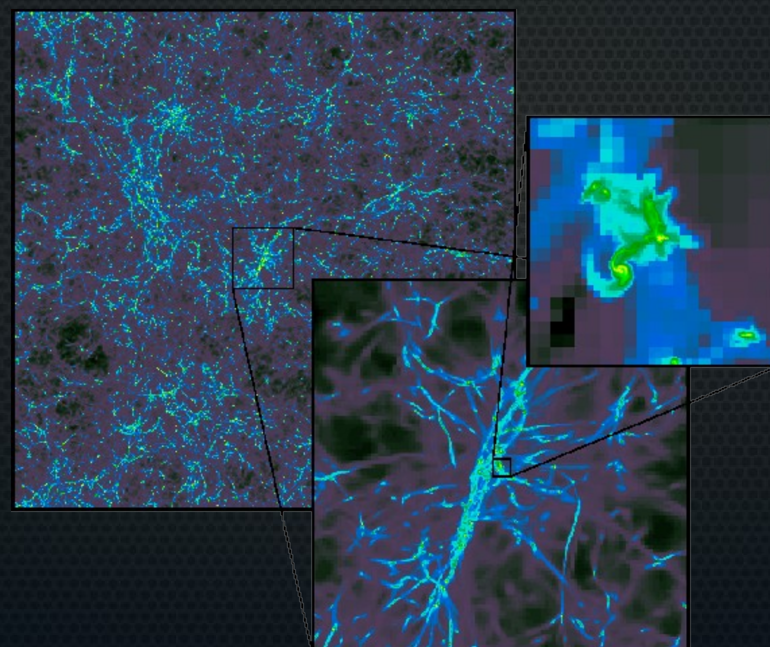
$$\frac{\partial}{\partial t}\int_{x_1}^{x_2} \boldsymbol{u}\,\mathrm{d}x + \int_{x_1}^{x_2} \frac{\partial \boldsymbol{f}}{\partial x}\mathrm{d}x = 0$$

Smoothed Particle Hydrodynamics



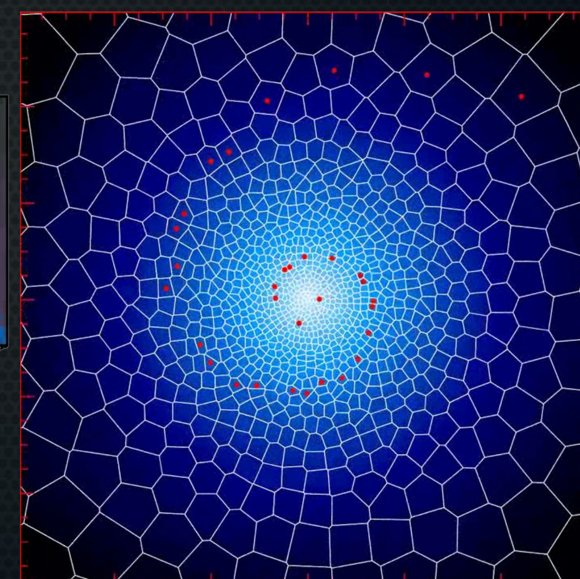
Gadget, Gasoline, ...

Adaptive Mesh Refinement



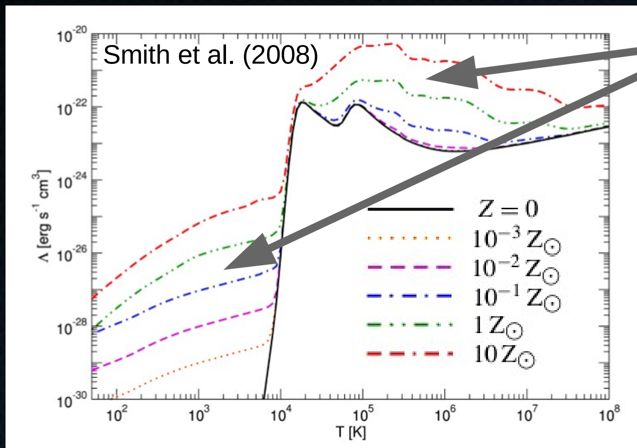
Enzo, H-ART, FLASH, RAMSES, ...

Moving Mesh



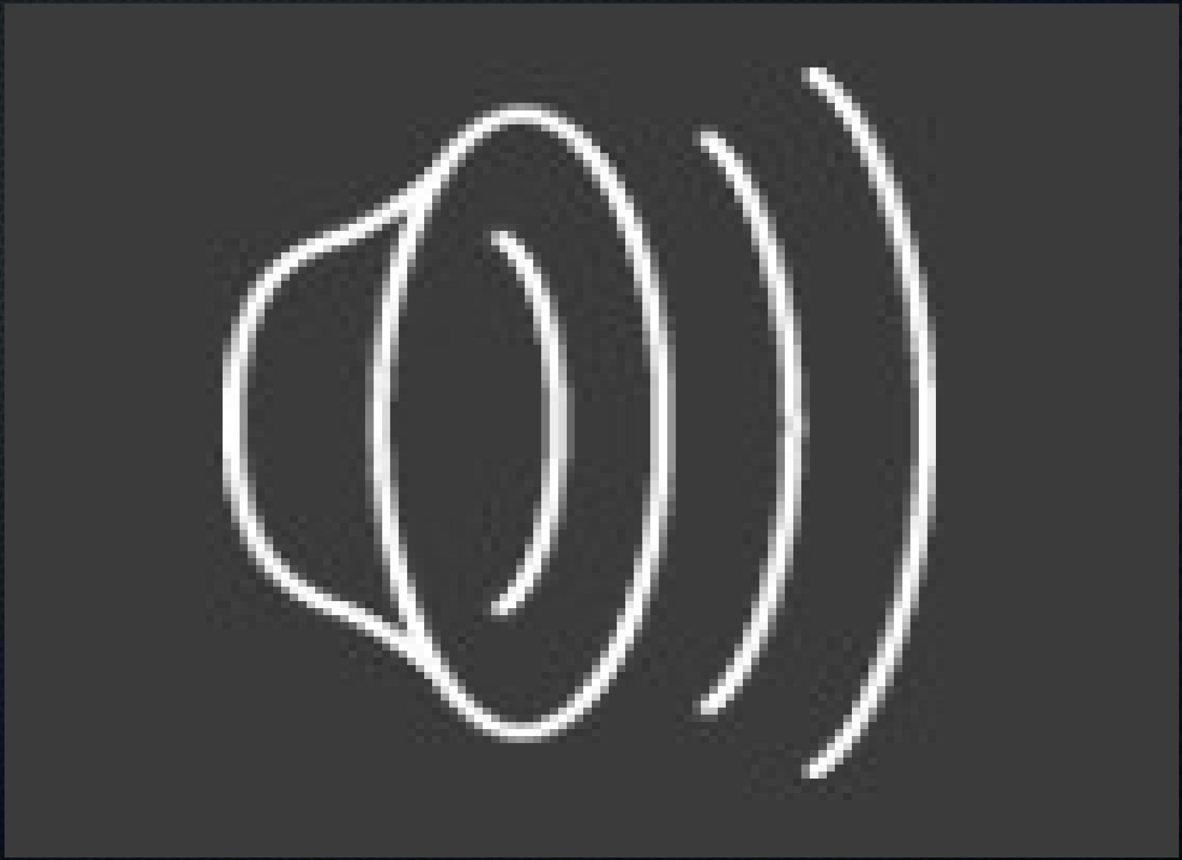
Arepo

Cooling, Star Formation, Feedback...



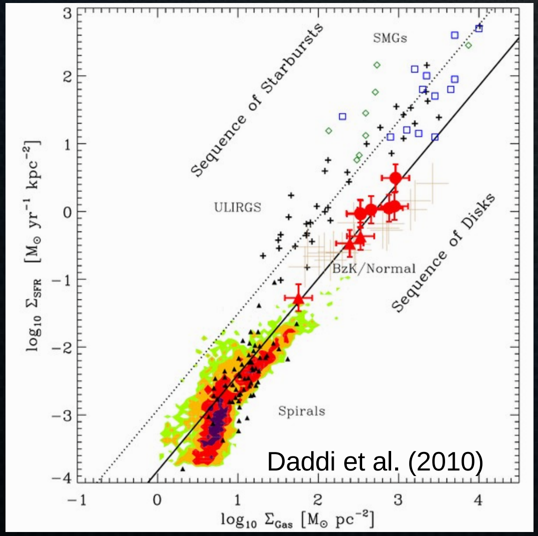
Metal-dependent cooling: Λ(T, x_e, UVB(z), Z)

Supernova (and/or AGN) feeback prescription



Star Formation calibrated to Kennicutt-Schmidt relation

$$\dot{\rho}_{\rm SF} = \epsilon_\star \frac{\rho_{\rm H_2}}{t_{\rm freefall}} \propto f_{\rm H_2}\, \rho_{\rm gas}^{3/2}$$

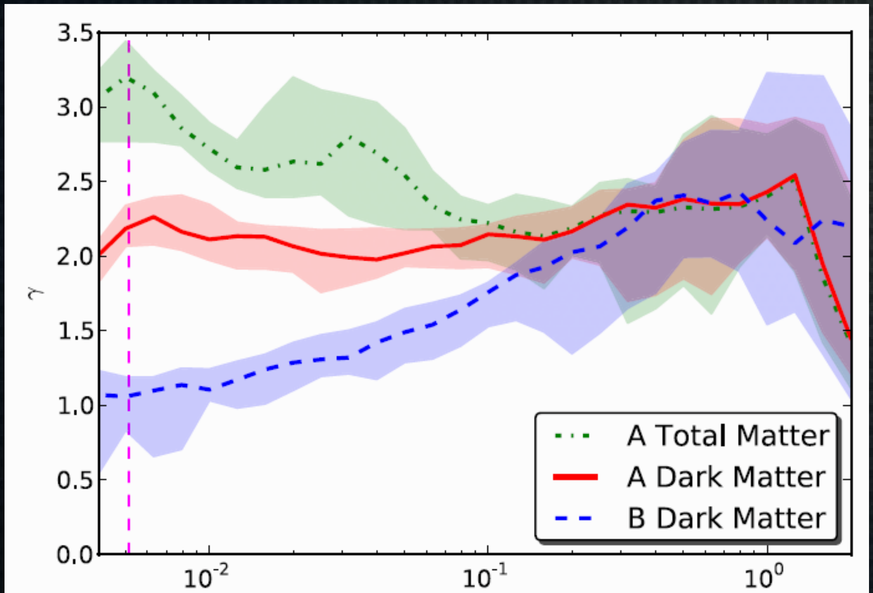


Beyond DM-only: including baryonic physics

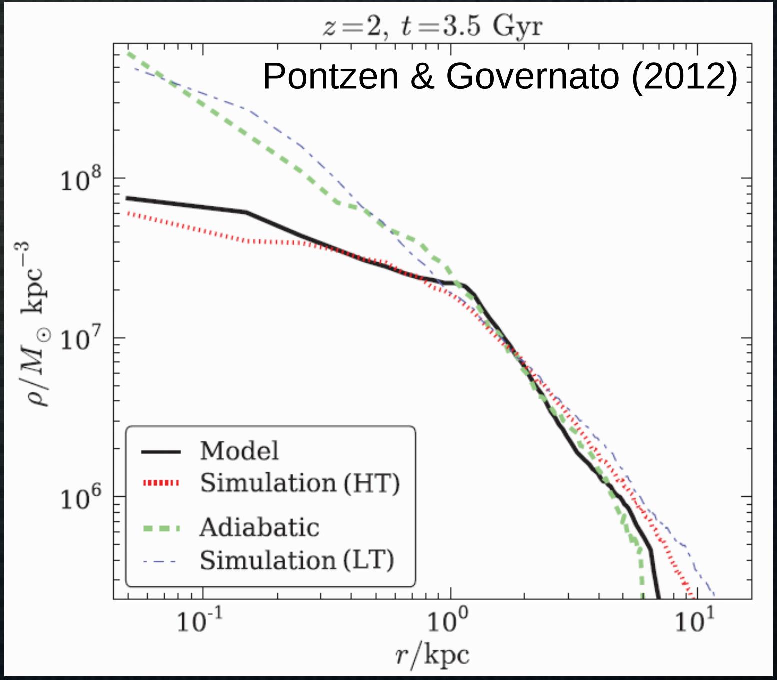
Often not even the sign of the effect is known...

Adiabatic contraction steepens the DM profile and **increases central DM densities**.

Impulsive supernova (or AGN) feedback **removes DM from the center** and flattens the DM cusp.



Zemp et al. (2012)

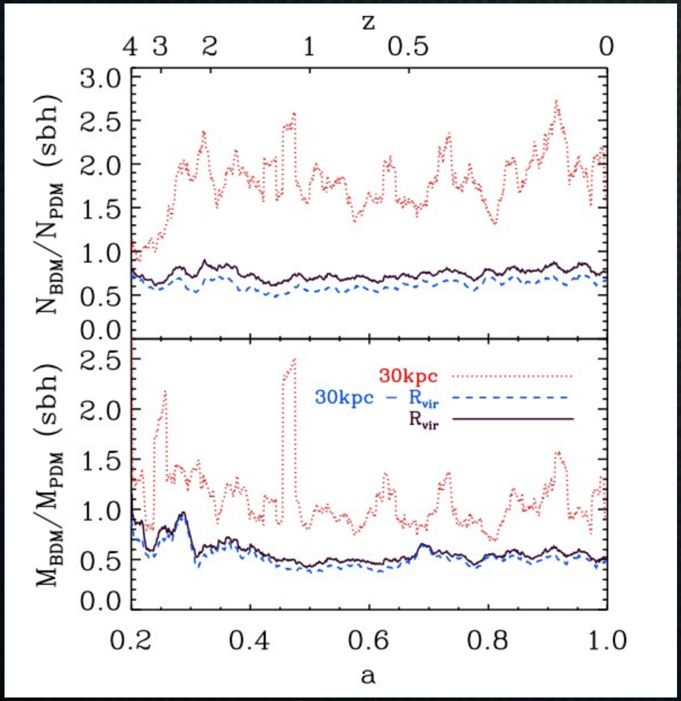


Beyond DM-only: including baryonic physics

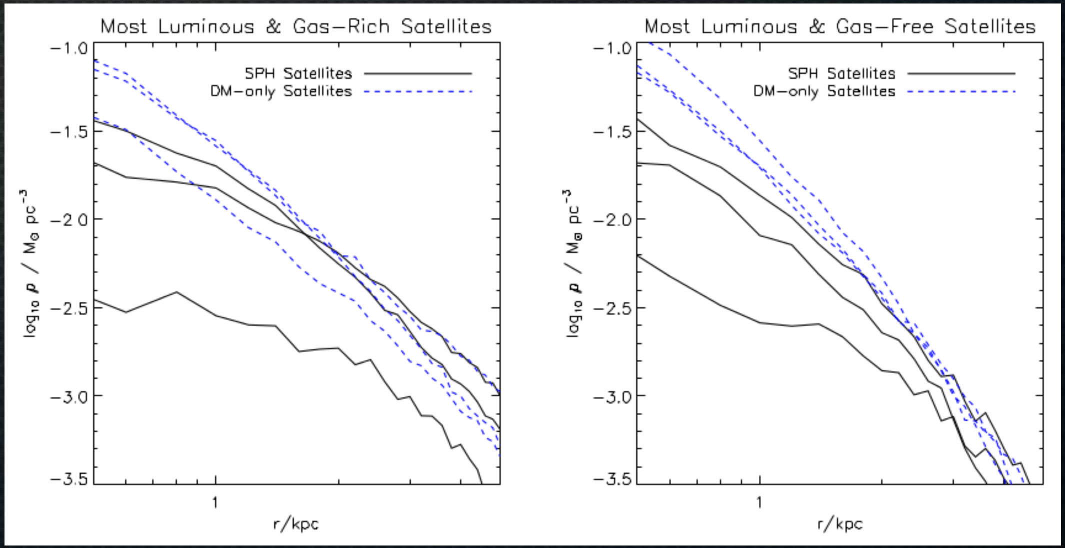
Often not even the sign of the effect is known...

Baryonic condensation in the centers of satellite halos makes them more resilient to tidal disruption and **increases abundance of inner subhalos**.

The deeper host halo potential, satellite cusp removal, and disk passages enhance tidal stripping and **reduce the number of surviving subhalos**.

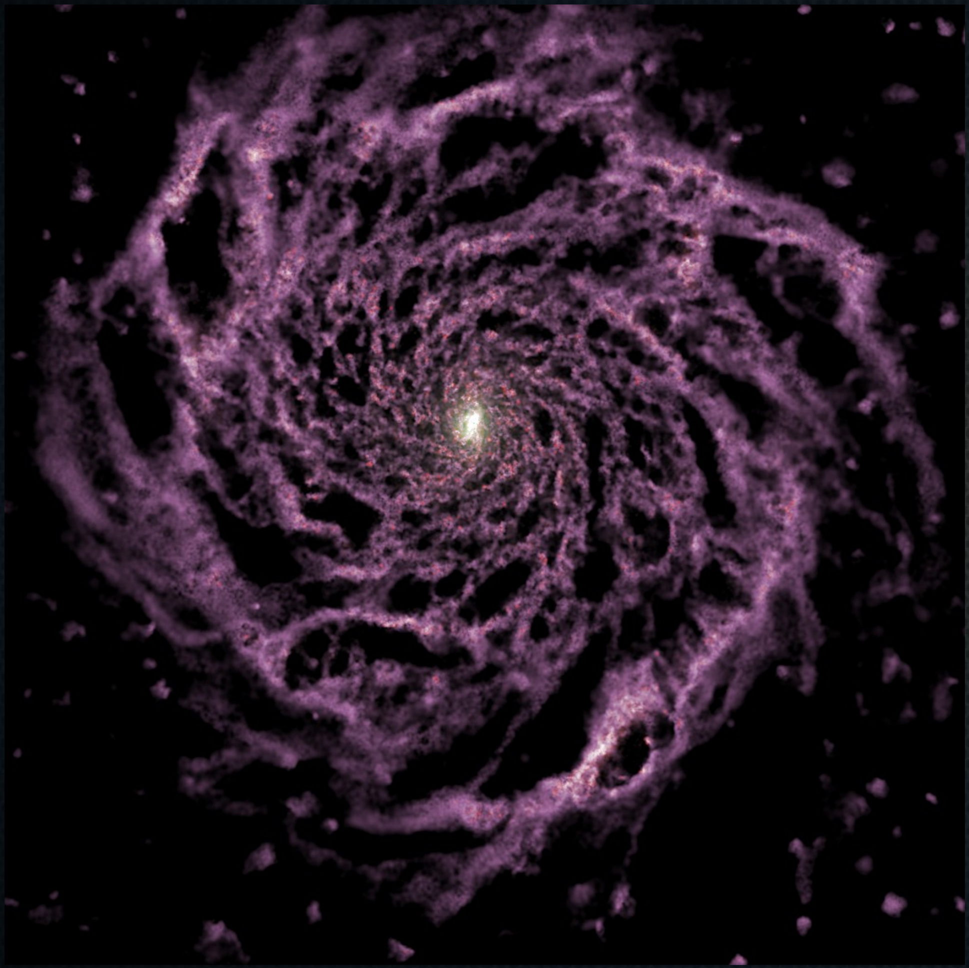


Romano-Diaz et al. (2010)



Zolotov et al. (2012)

The Eris Simulation



For more details see Guedes et al. 2011

Cosmological SPH Zoom-in Simulation

7 million DM particles (10^5 $M_\odot$)
3 million gas particles (2×10^4 $M_\odot$)
8.6 million star particles ($4\text{-}6\times10^3$ $M_\odot$)

- radiative cooling
  (Compton, atomic, low-T metallicity-dependent)
- heating from cosmic UV
  (~ Haardt & Madau 1996)
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  - threshold: n_{SF} = 5 atoms/cm^3
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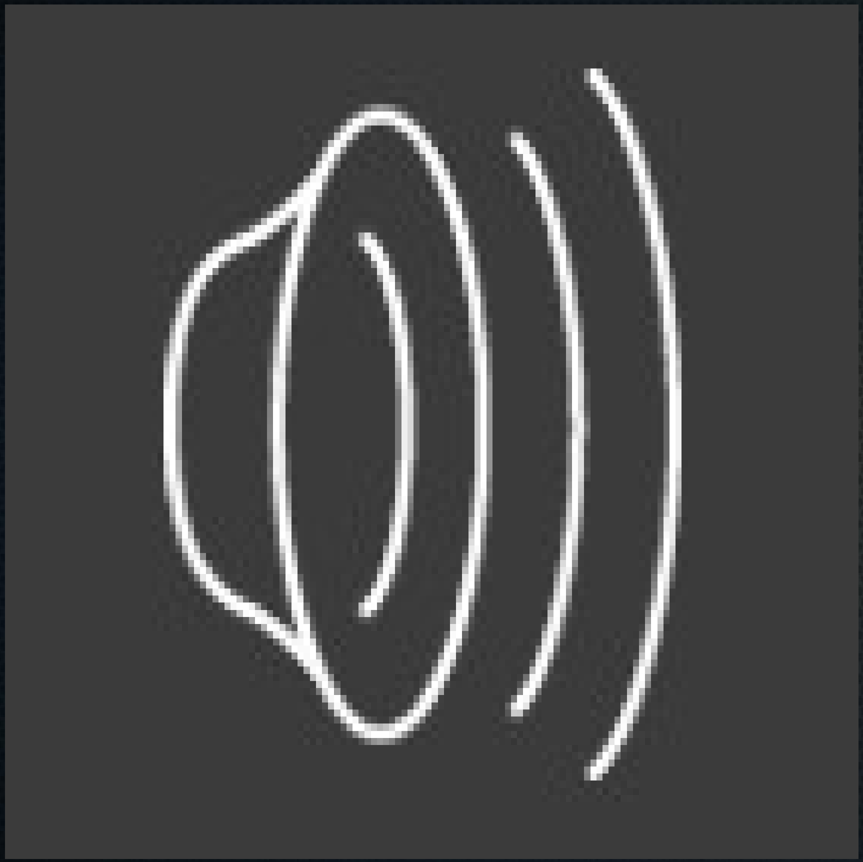
Results in a realistic looking Milky-Way-like spiral disk galaxy at z=0.

The Eris Simulation



For more details see Guedes et al. 2011

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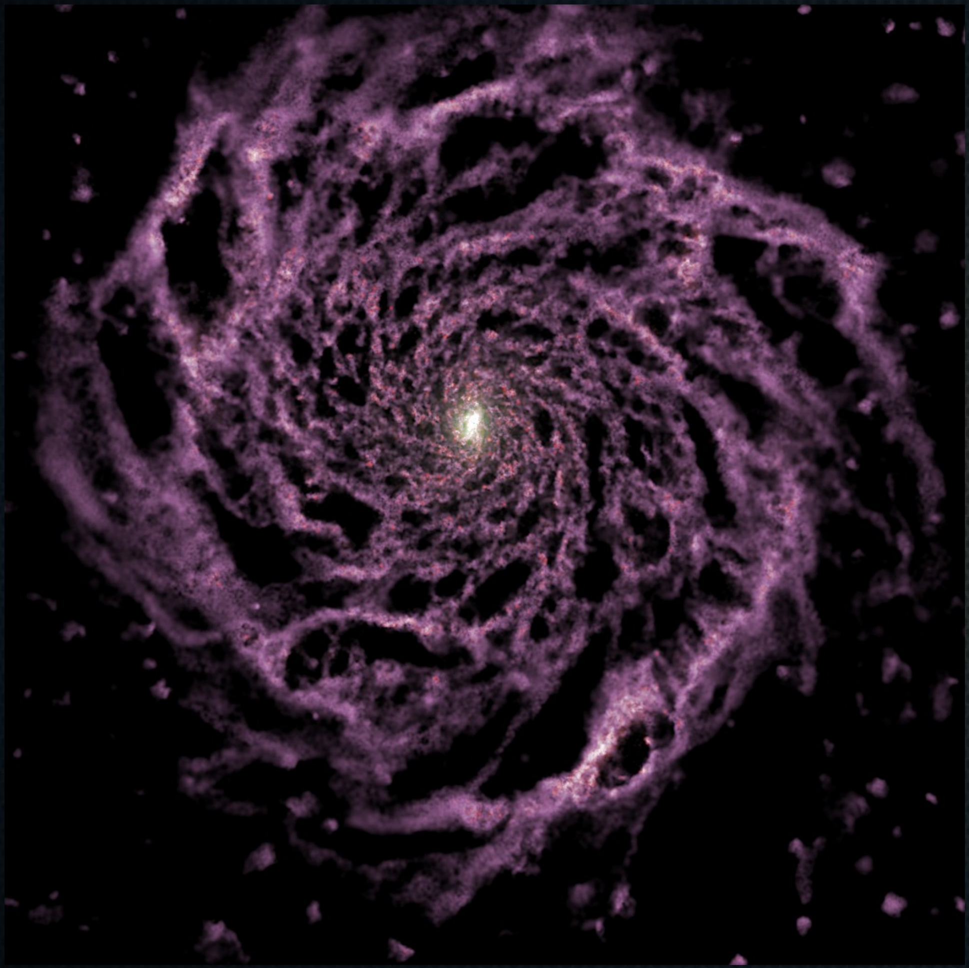

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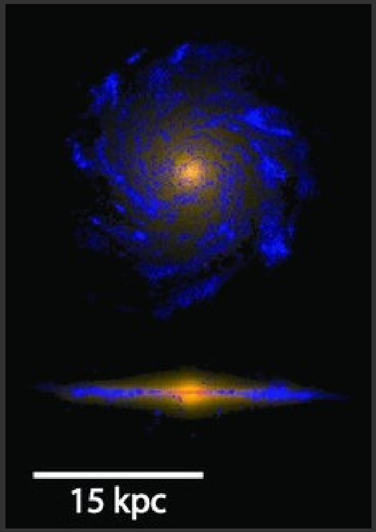
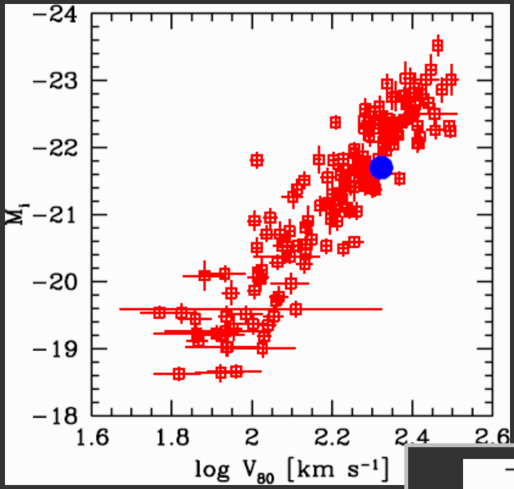
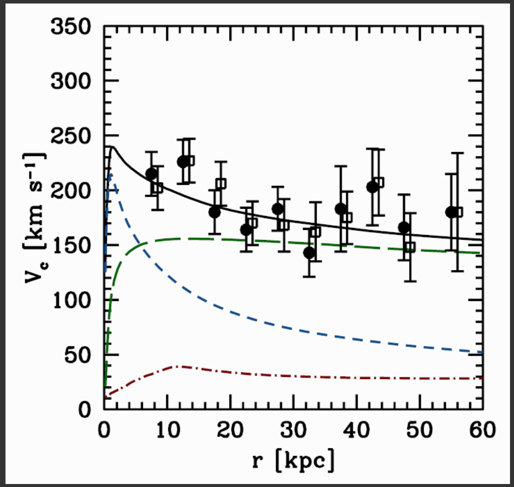
The Eris Simulation

I-band (Sunrise) Bulge/Disk = 0.35, consistent with Sb, Sbc galaxies (Graham & Worley 2008).

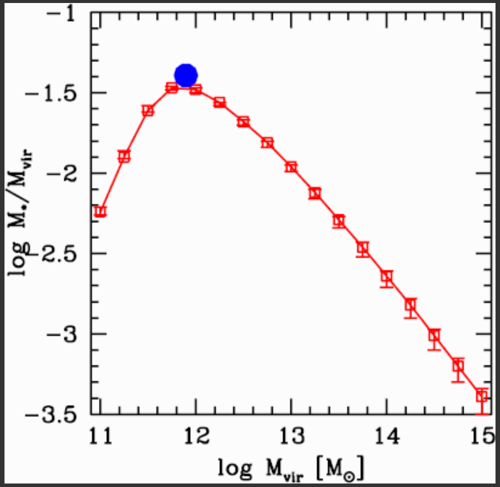


Lies on Tully-Fisher relation from Pizagno et al. 2007.





Slowly falling rotation curve, which matches Xue et al. (2008) SDSS measurement using BHB stars out to 60 kpc.



Lies on Behroozi et al. (2010) z=0 stellar-mass-halo-mass relation.

Baryonic Effects on Dark Matter

Two Examples:

1) A Baryonic Solution to „Too Big To Fail"

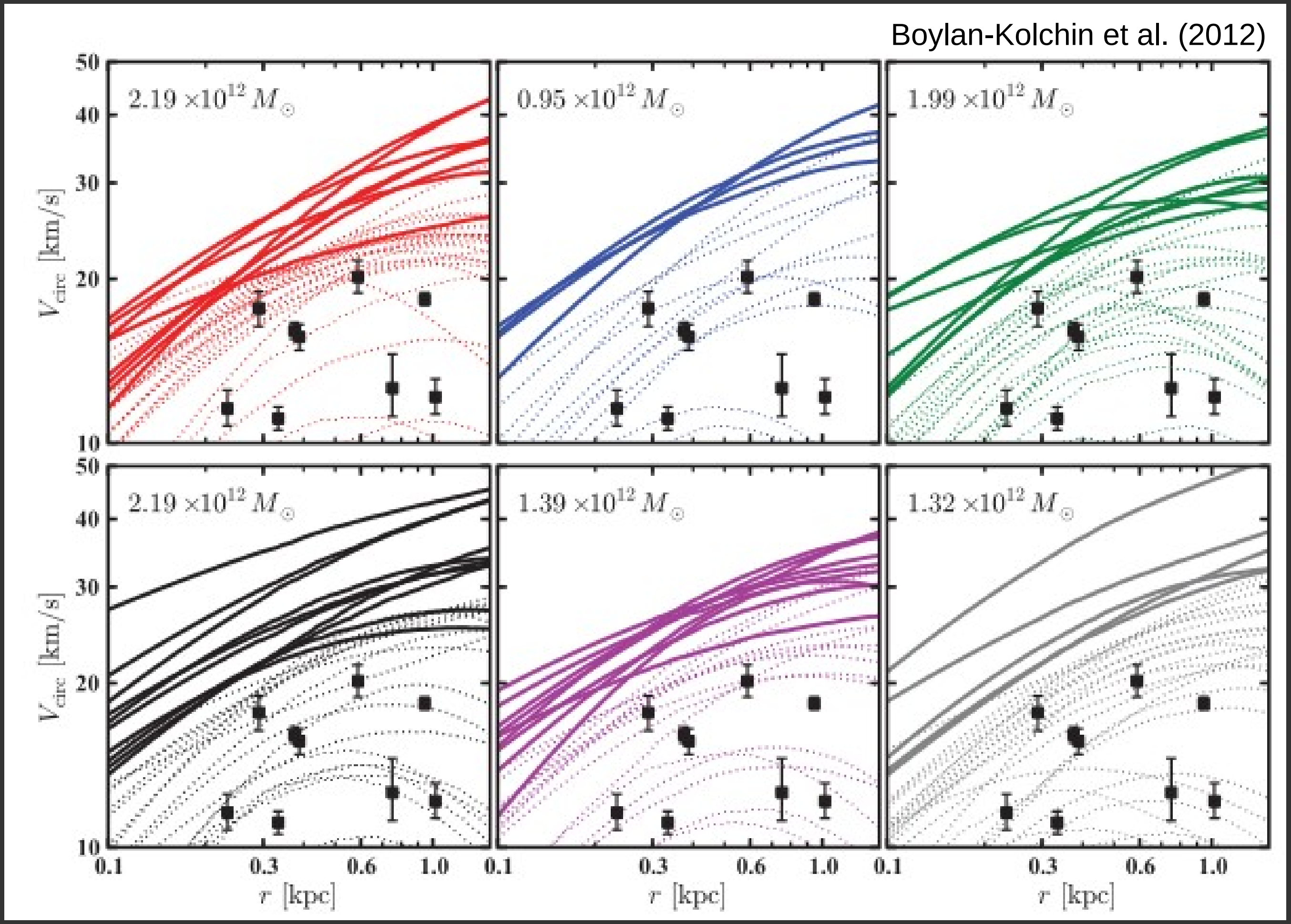
Brooks, Kuhlen, Zolotov, & Hooper (2012), arXiv:1209.5394

2) An Offset Dark Matter Density Peak in the Galactic Center?

Kuhlen et al. (2012), arXiv:1208.4844

II. A Baryonic Solution to Too Big To Fail

Too Big To Fail Problem

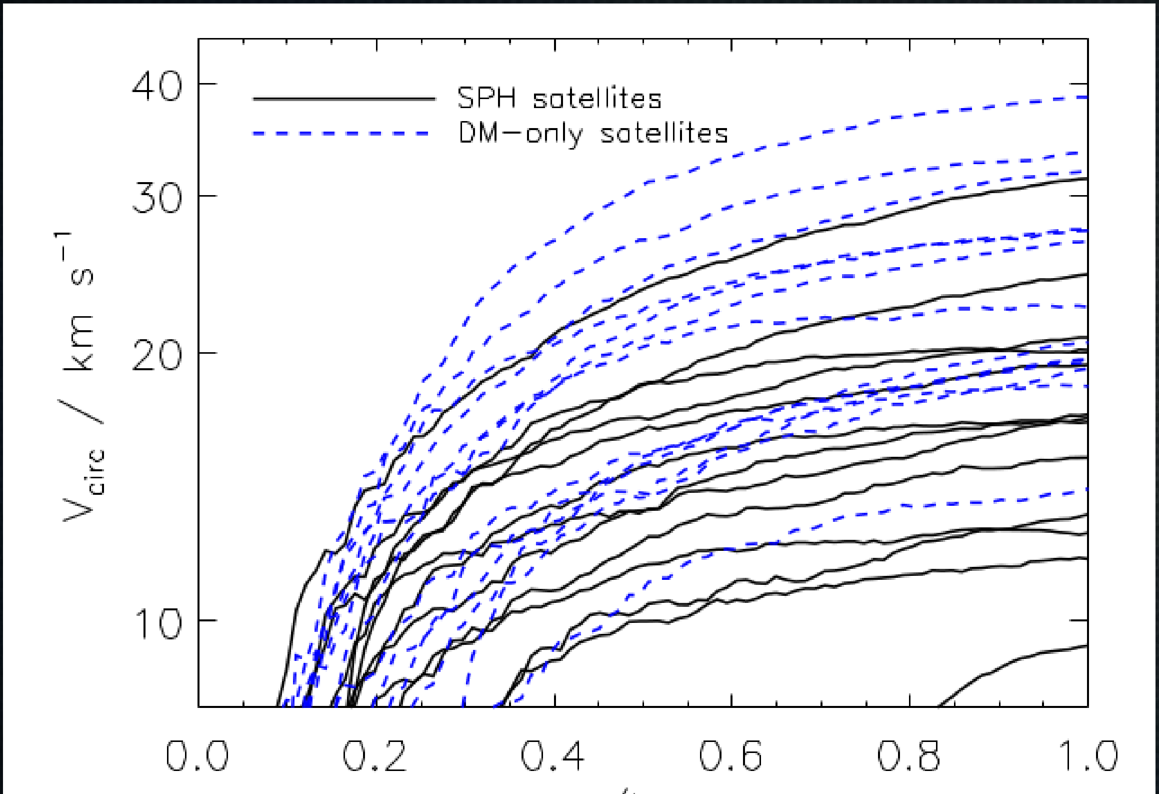


Zolotov et al. (2012)

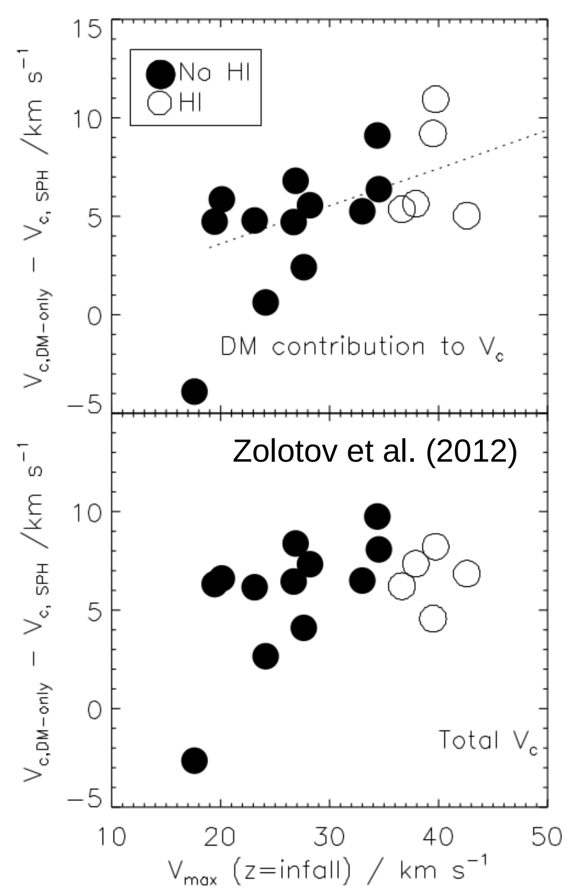
II. A Baryonic Solution to Too Big To Fail

Simulations similar to Eris

[GASOLINE SPH code, slightly poorer resolution, same feedback prescription, H_2-regulated SF; see Zolotov et al. 2012 & Brooks & Zolotov 2012 for details.]



Zolotov et al. (2012)



A prescription to apply to DM-only simulations:

$$\Delta(v_{1\mathrm{kpc}}) = 0.2 v_{\mathrm{infall}} - 0.26\ \mathrm{km\ s^{-1}}$$

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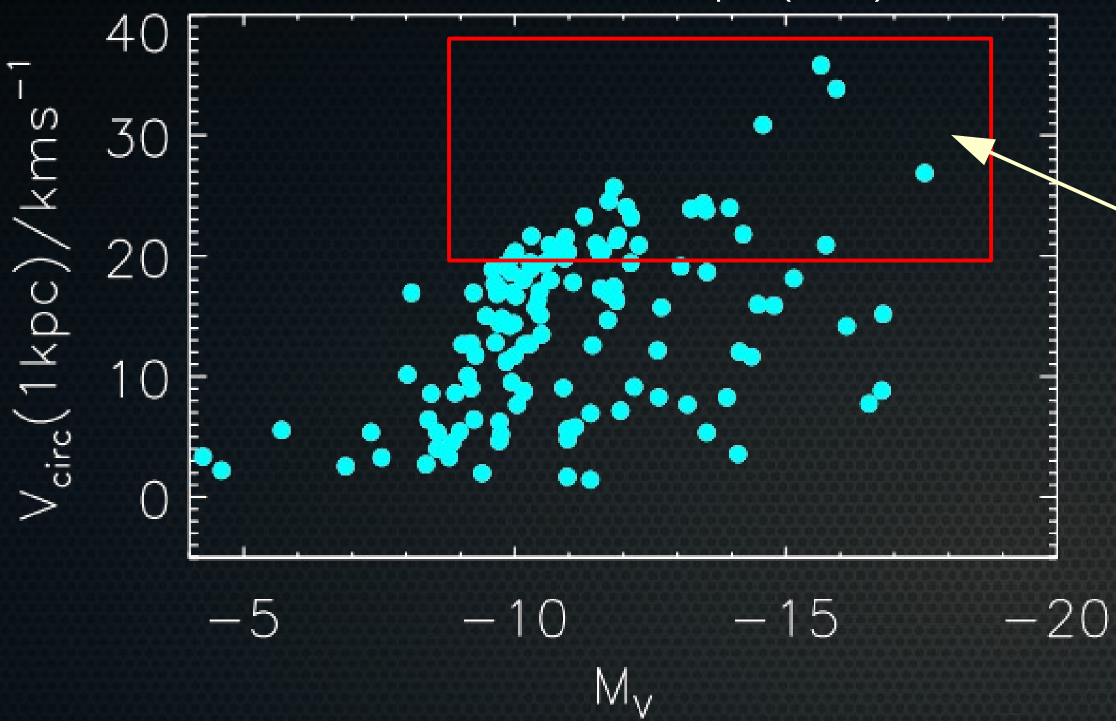
Brooks, Kuhlen, Zolotov, & Hooper (2012)



$$\frac{M_{star}}{M_\odot} = 0.018\left(\frac{v_{infall}}{km\ s^{-1}}\right)^6$$

$$\log_{10}\left(\frac{M_{star}}{M_\odot}\right) = -0.38 - 4.63 M_V$$

In Via Lactea II, there are 28 bright satellites with V_{1kpc} > 20 km/s.

In the Milky Way maybe 5:
LMC, SMC, Sag. (being disrupted), Ursa Minor, Draco

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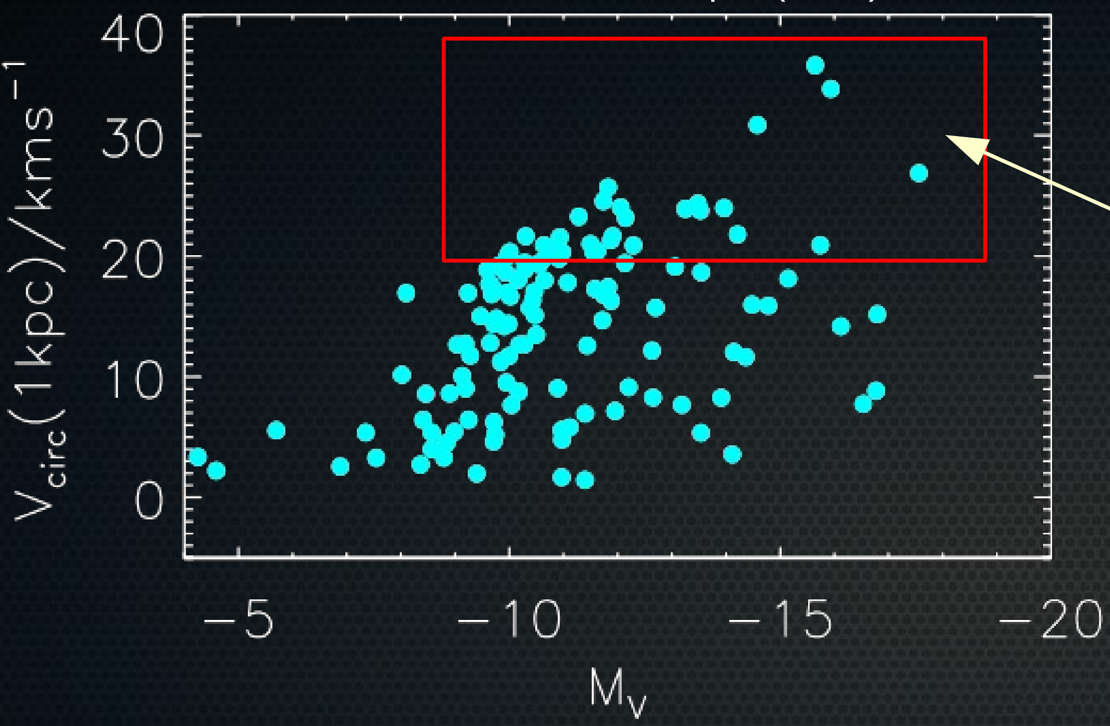

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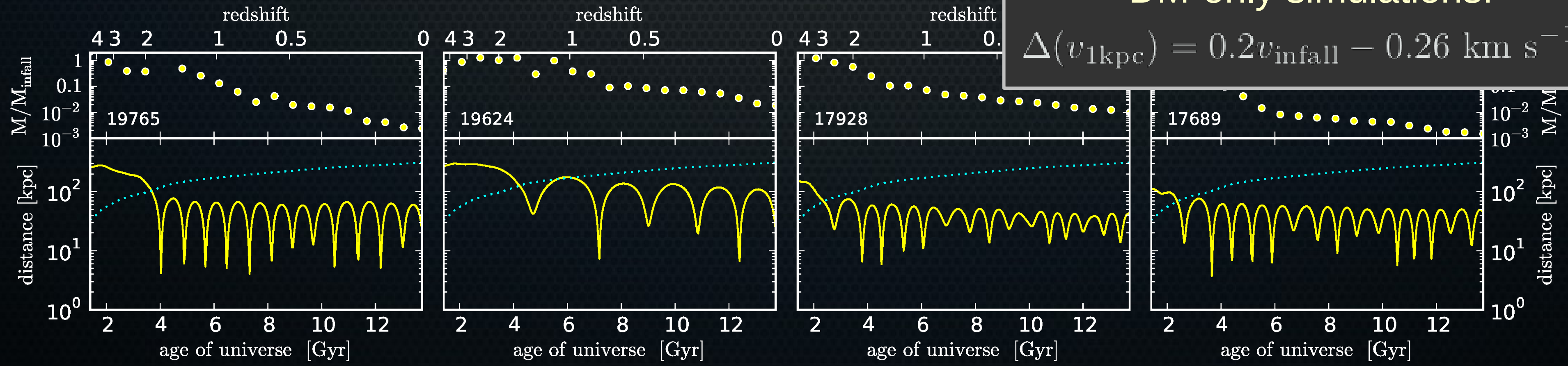

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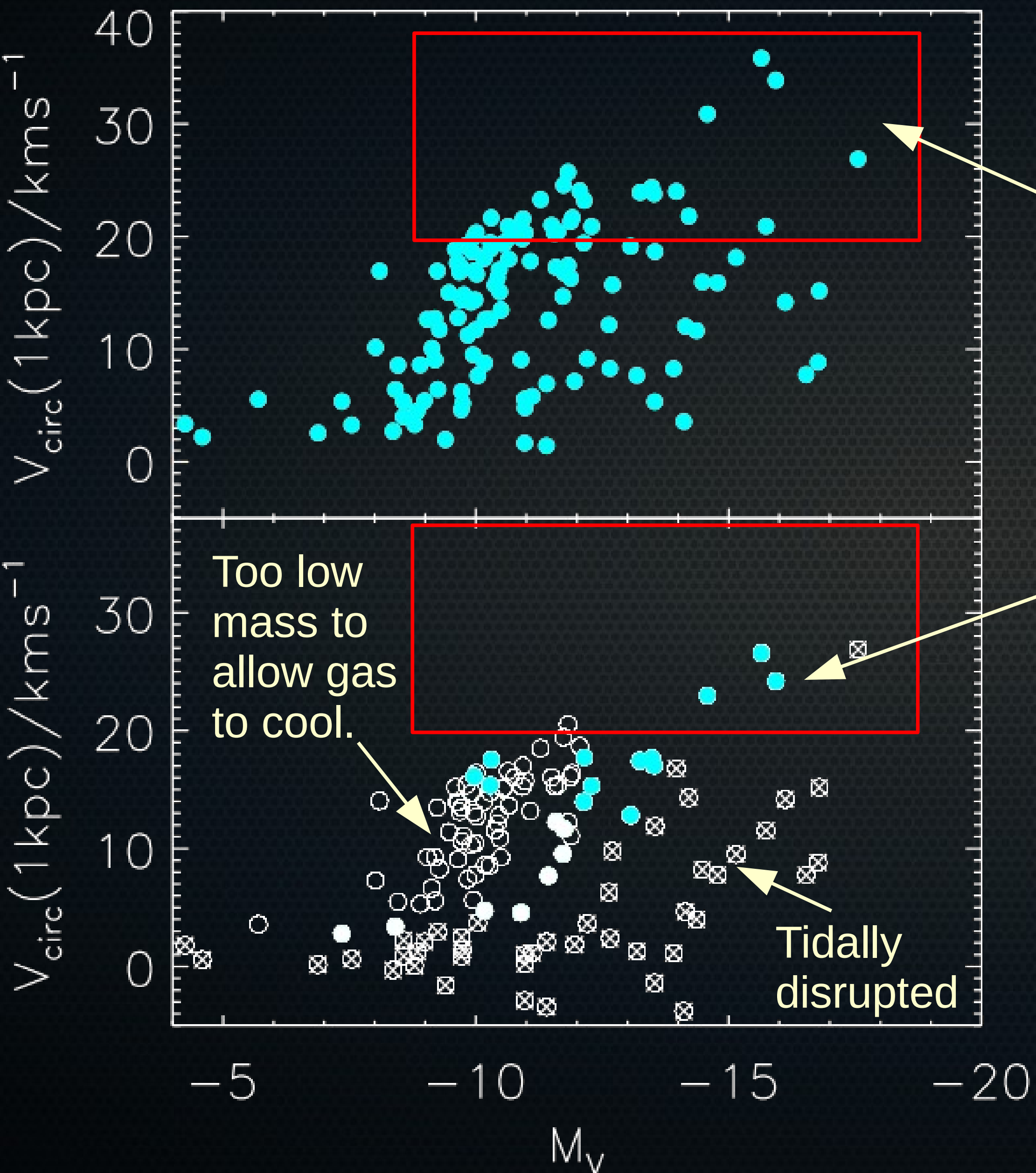

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In Via Lactea II, there are 28 bright satellites with V_{1kpc} > 20 km/s.

Number of satellites agrees with observtations after these ocrrections:

1) Apply Zolotov et al. (2012) prescription for V_{1kpc} reduction;
2) Subhalos that have a <20kpc pericenter passage and lose 90% of their mass are considered disrupted;
3) Subhalos must exceed z-dependent mass threshold (Okamoto et al. 2008) to allow gas to cool and form stars.

Baryonic Effects on Dark Matter

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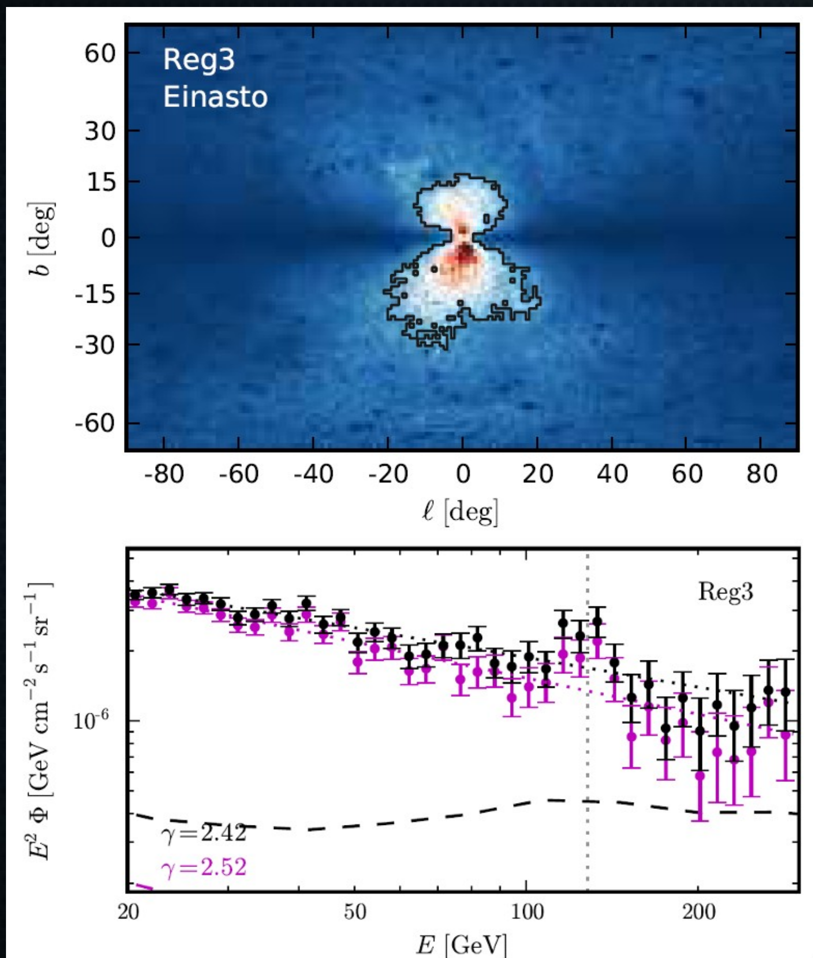
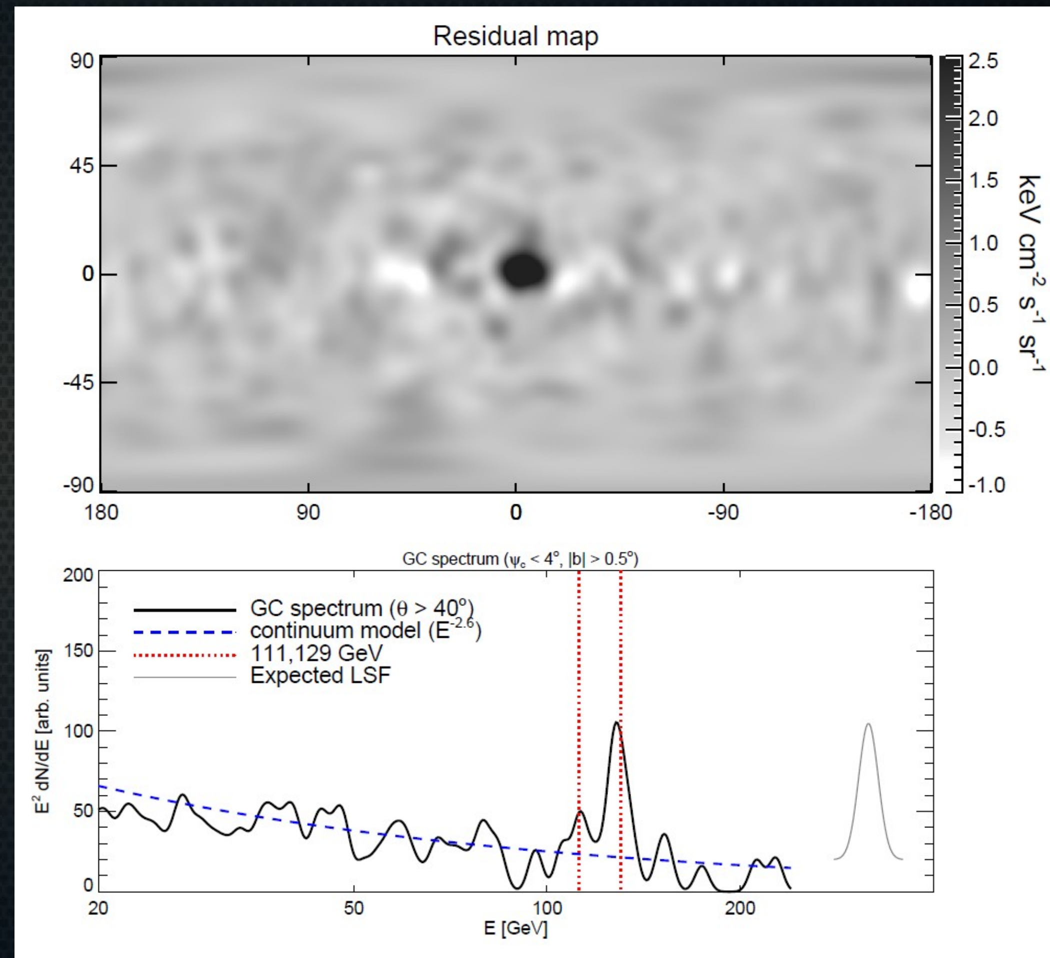
III. Baryonic Effects on DM at the Galactic Center

130 GeV Line from the Galactic Center

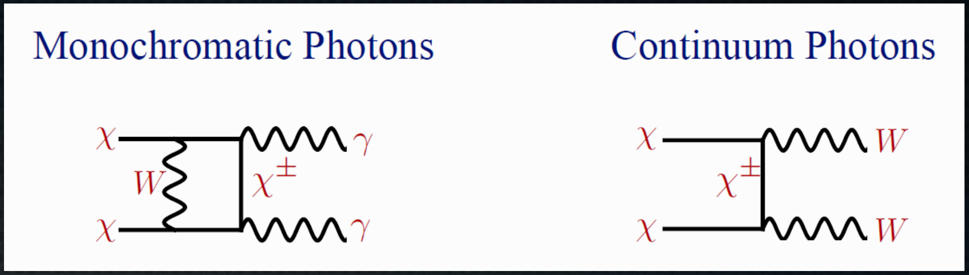


Weniger 2012



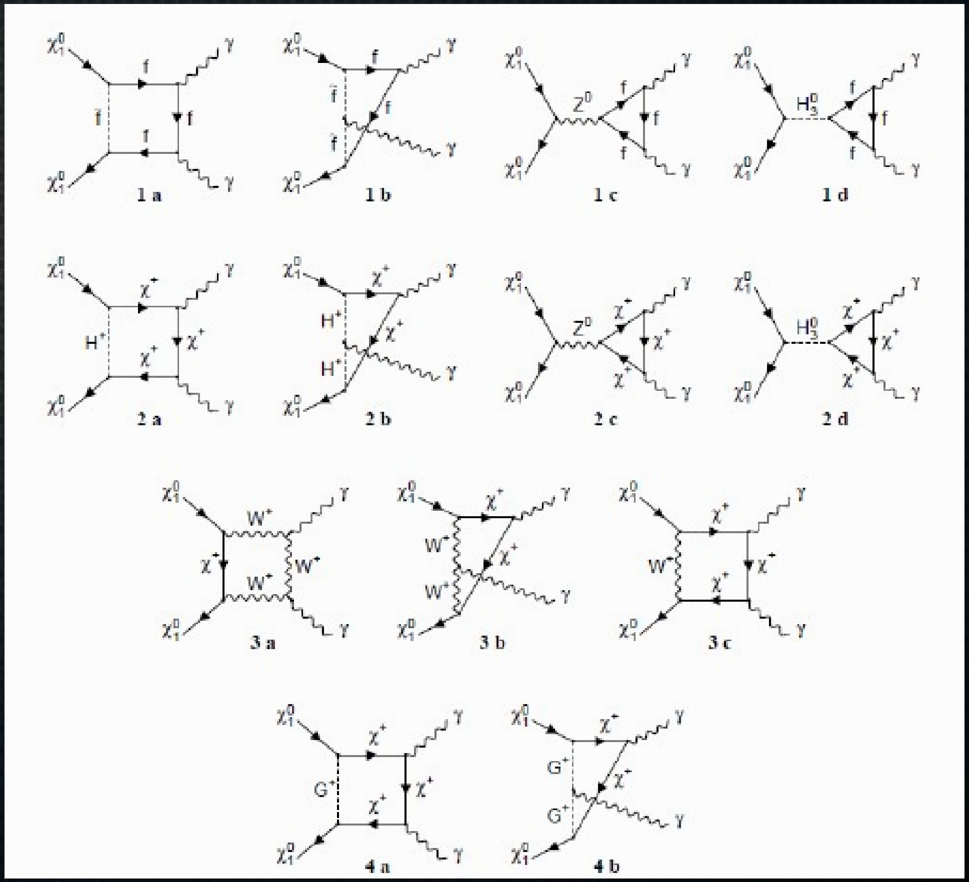
Su & Finkbeiner 2012

Is this DM annihilation?



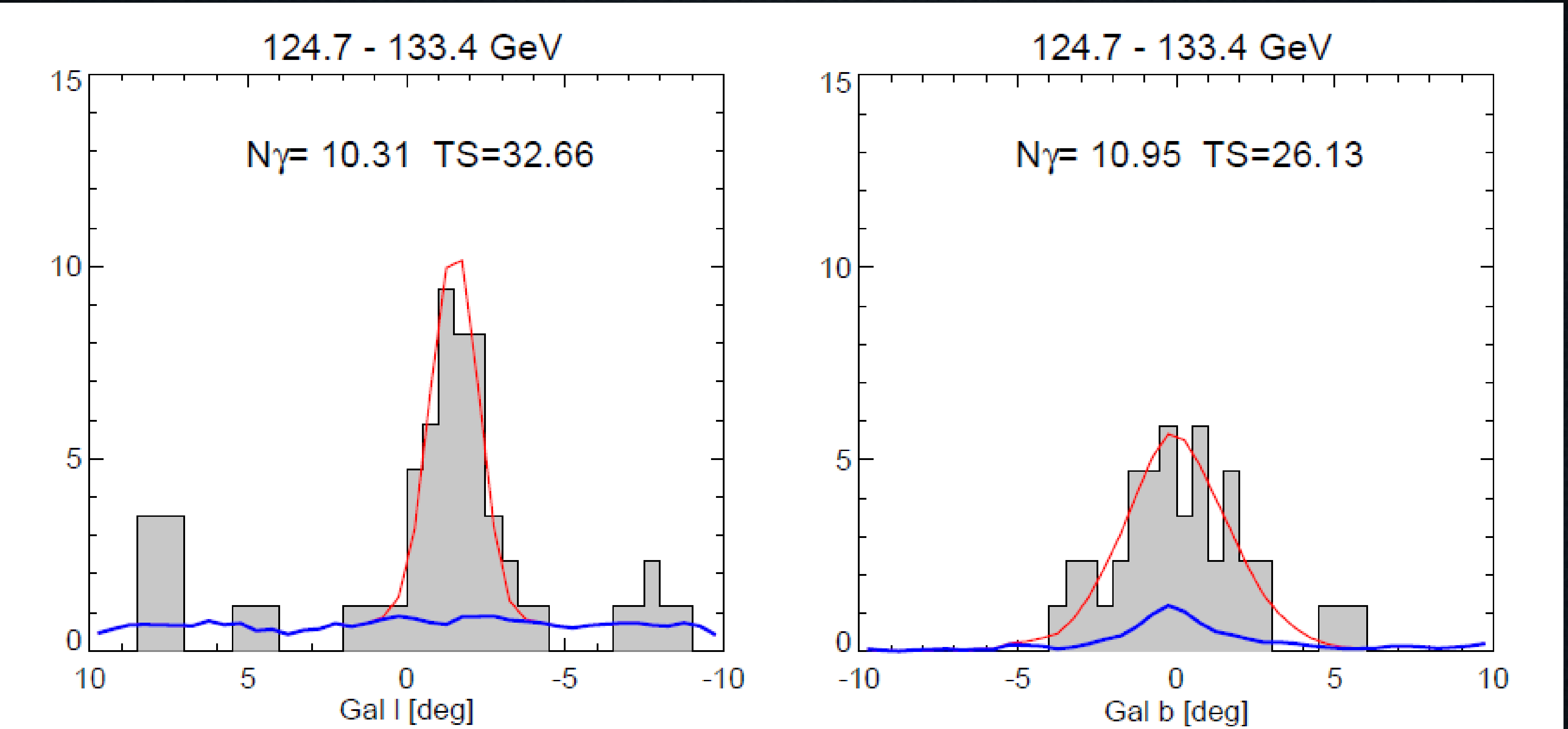
DM annihilation?

- 2-body annihilation: $\chi\chi \rightarrow \gamma\gamma,\ \gamma Z,\ \gamma h$
- Normally "loop suppressed" ($10^{-2} - 10^{-4}$) compared to continuum radiation.
- But models with enhanced lines exist, e.g.:
  Singlet DM (Profumo et al. 2010)
  "Higgs in Space" (Jackson et al. 2010)



Bergström & Ullio 1997

The line is not exactly at the Galactic Center



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The significance of the signal is maximized at (ℓ,b) = (-1.5º,0º), or about **200 projected pc** from Sgr A*.

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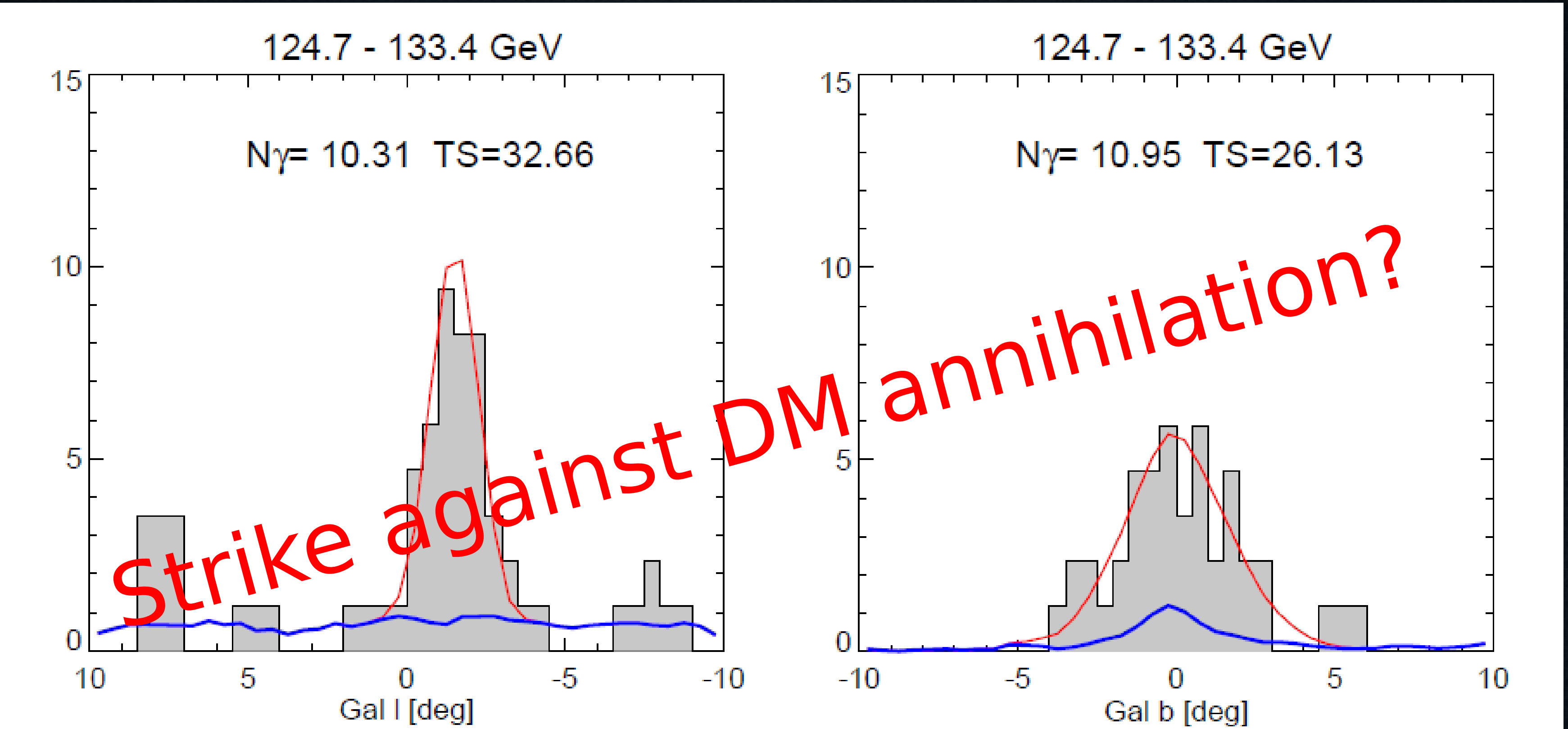

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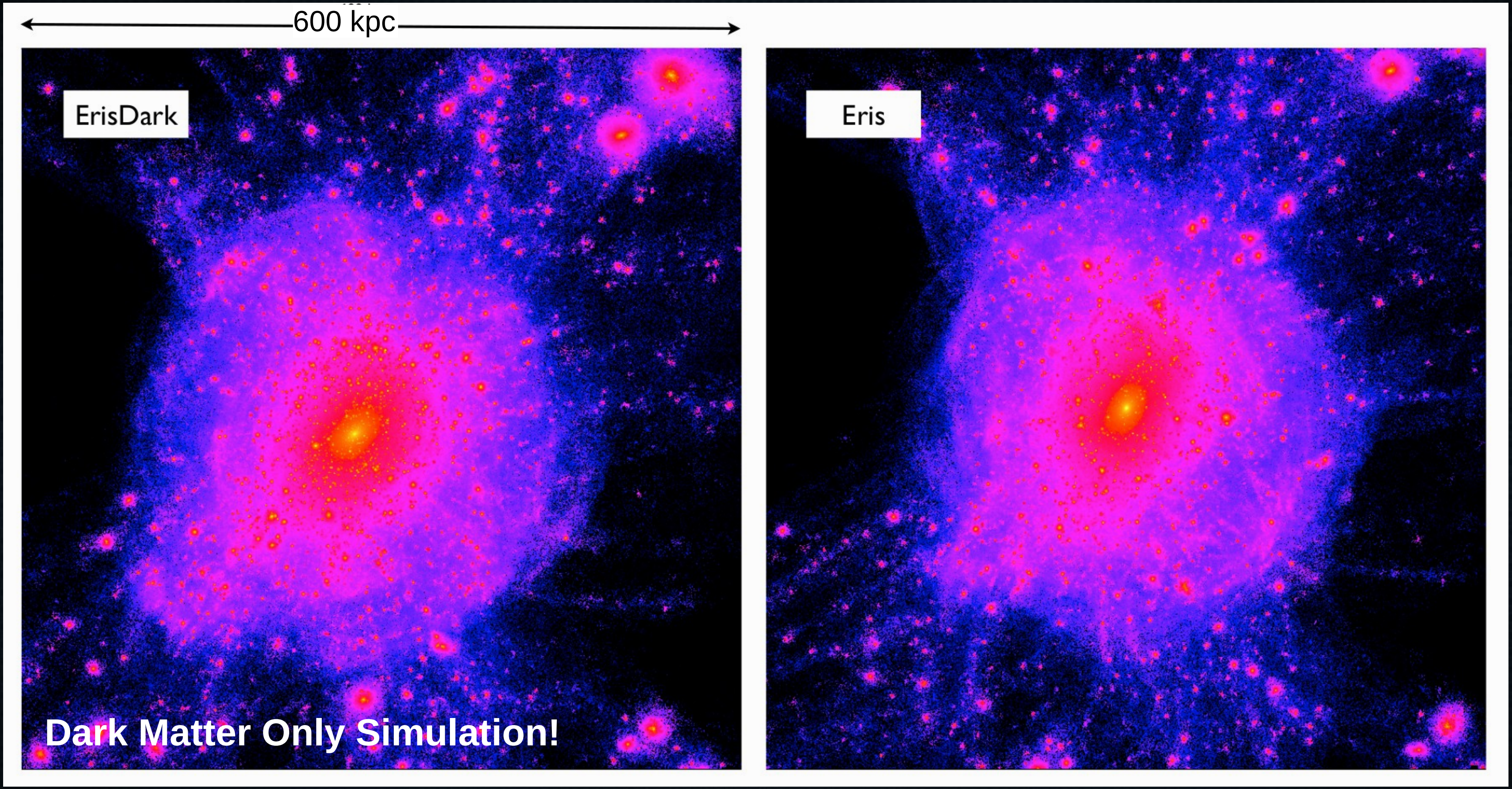
Eris & ErisDark

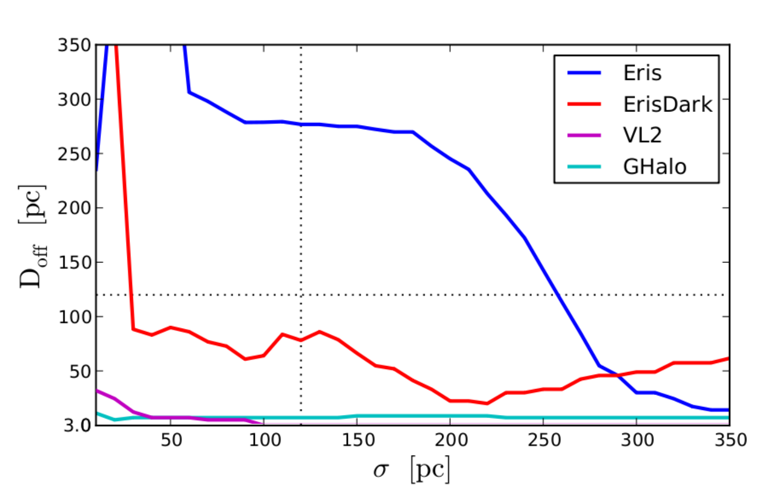


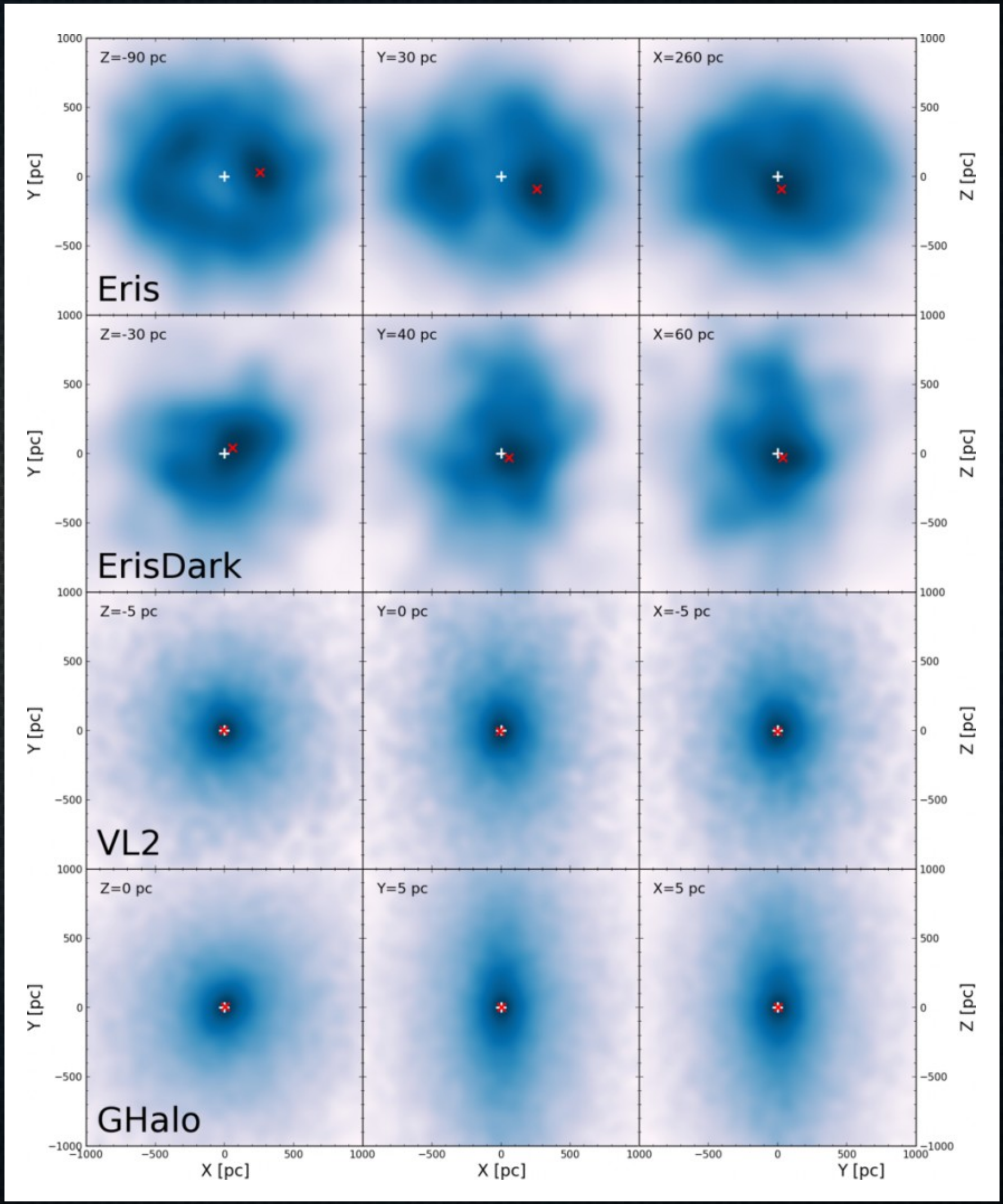
ErisDark has the same initial conditions as Eris, except that all of the matter is treated as dark matter. (Pillepich et al., in prep.)

DM offset in Eris

In the dissipational simulation (Eris), the maximum of the DM density is displaced from the minimum of the potential (dynamical center).

The DM-only runs show no such offset (to within one grav. softening length).



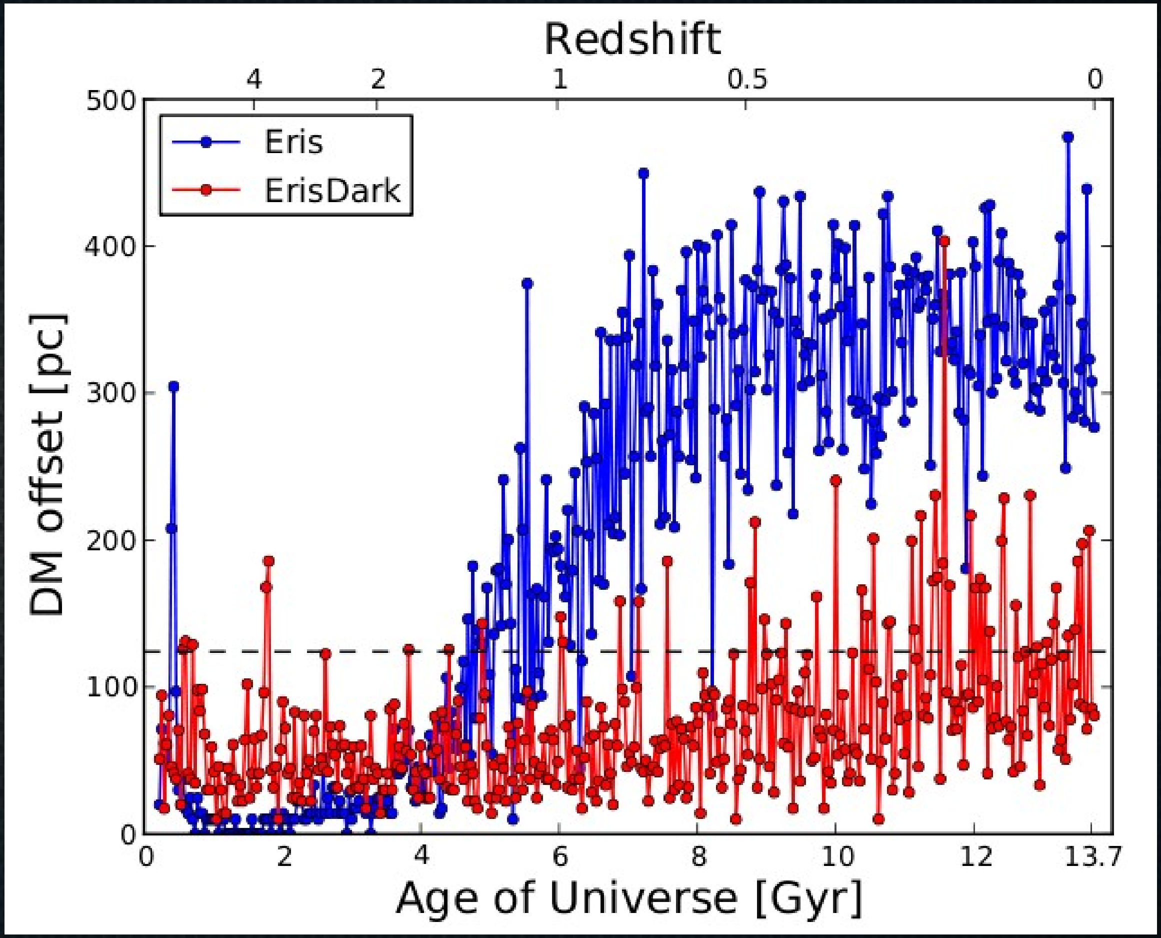


Formation and Evolution of the Offset

The offset is no fluke – it appears around z=1.5 and persists afterwards.

$\langle D_{off} \rangle$ = 340 pc (almost 3 ϵ_{soft}).

In ErisDark the offset remains below ~1ϵ_{soft}.



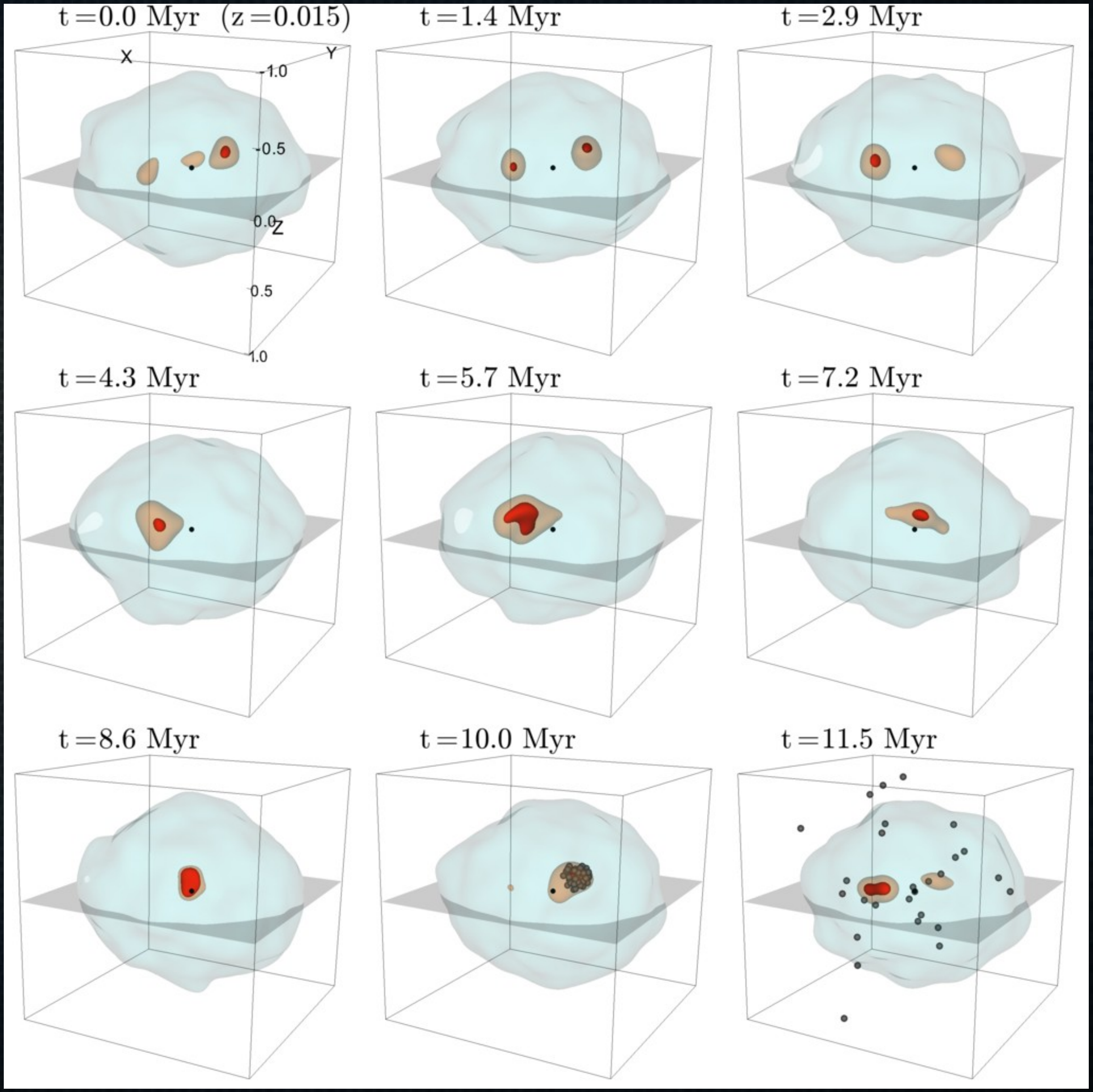
Formation and Evolution of the Offset

Eris output are spaced ~35 Myr – too long for dynamical analysis.

High output cadence re-run of the last few hundred Myr of Eris.

Typically close to the disk plane:
<ΔR> = 340 ± 51 pc
<Δz> = 64 ± 46 pc

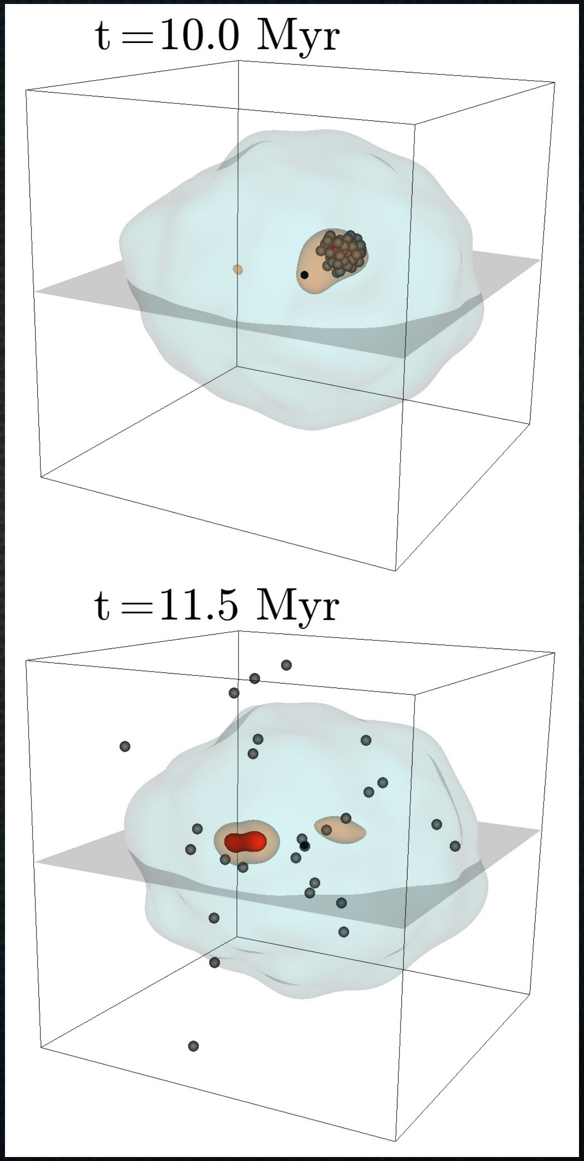
Not stationary.
Not coherent.
Sometimes multiple peaks.



Possible Explanations

Particles within 1 ϵ_{soft} of the offset peak at one time are no longer part of the offset peak as short as 1.5 Myr later.

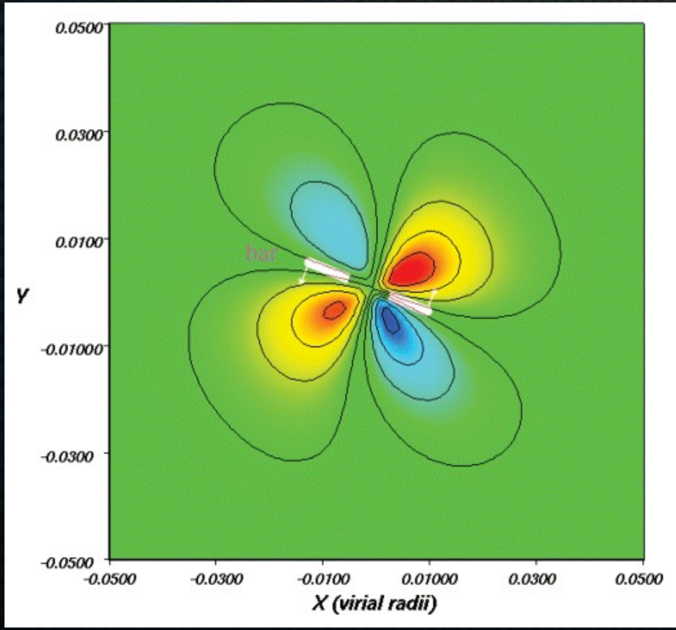
Not a coherent, bound structure. Not an incompletely disrupted subhalo.



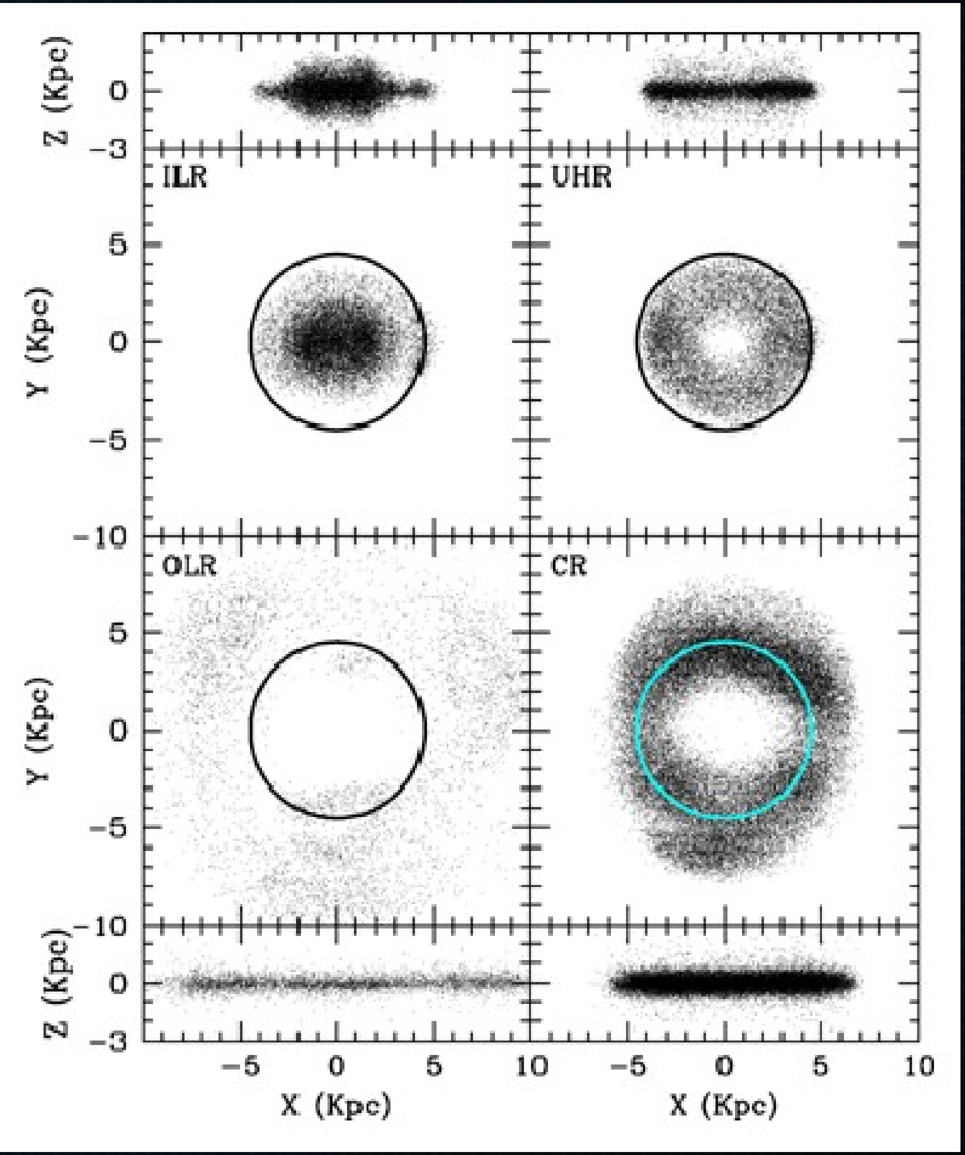
Possible Explanations

Resonant interaction with the stellar bar?

At times Eris has a very pronounced stellar bar. Maybe orbital resonances could lead to a density-wave-like excitation?



Weinberg & Katz 2002, 2007



Ceverino & Klypin 2007

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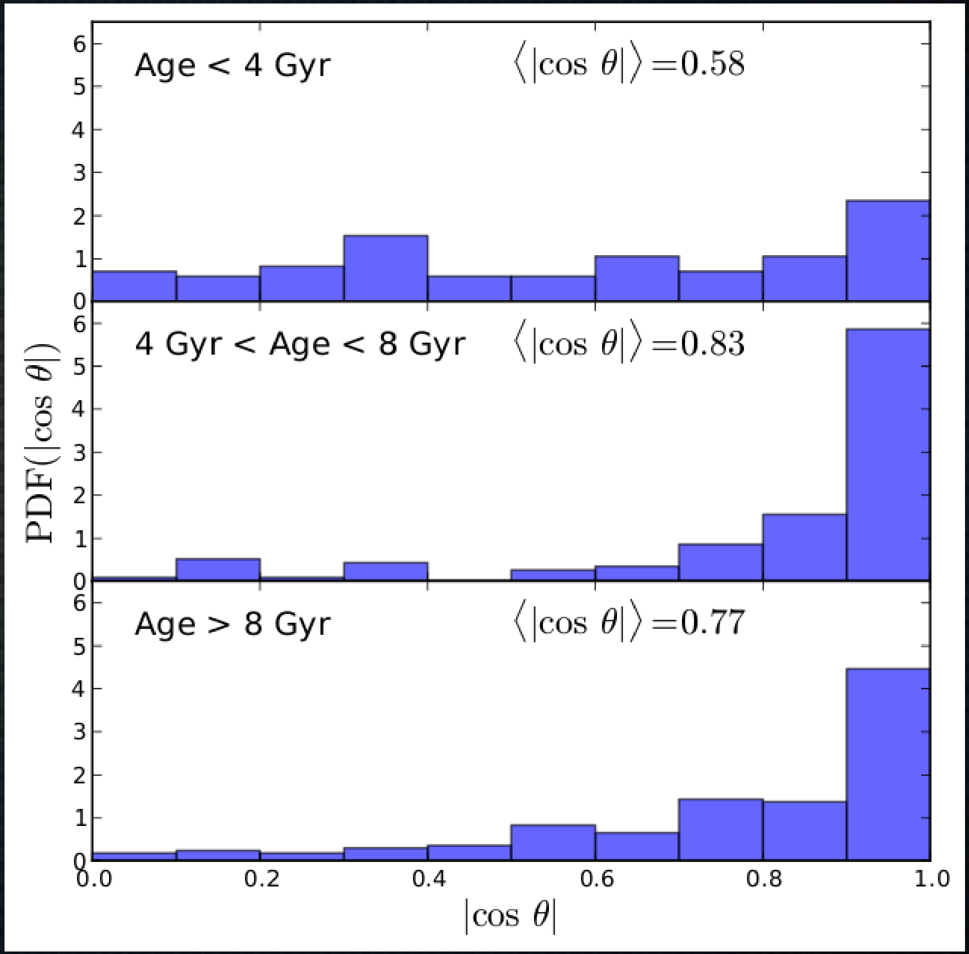
The direction of the DM offset is aligned with the orientation of the stellar bar in Eris.



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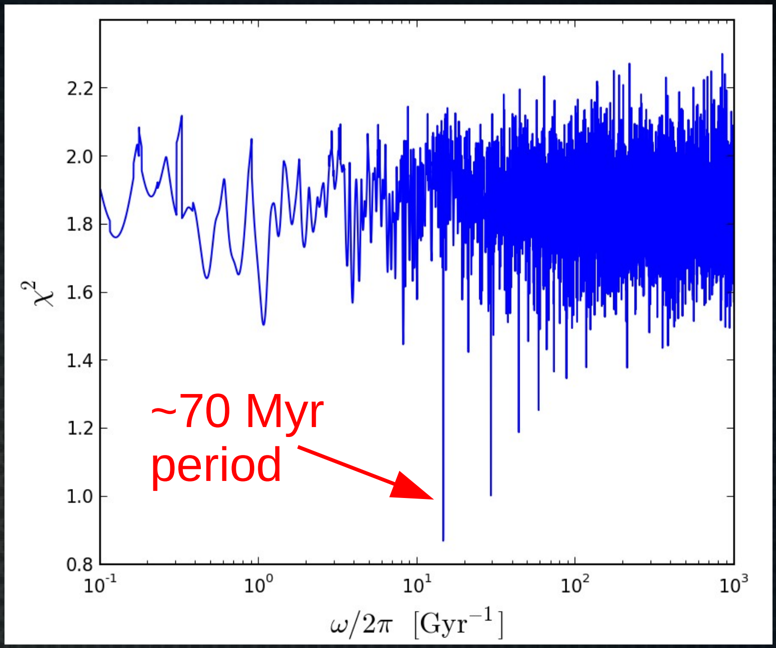
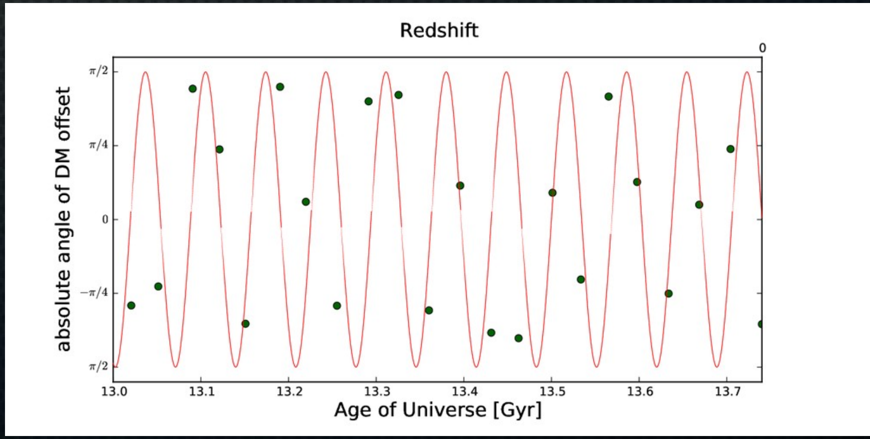
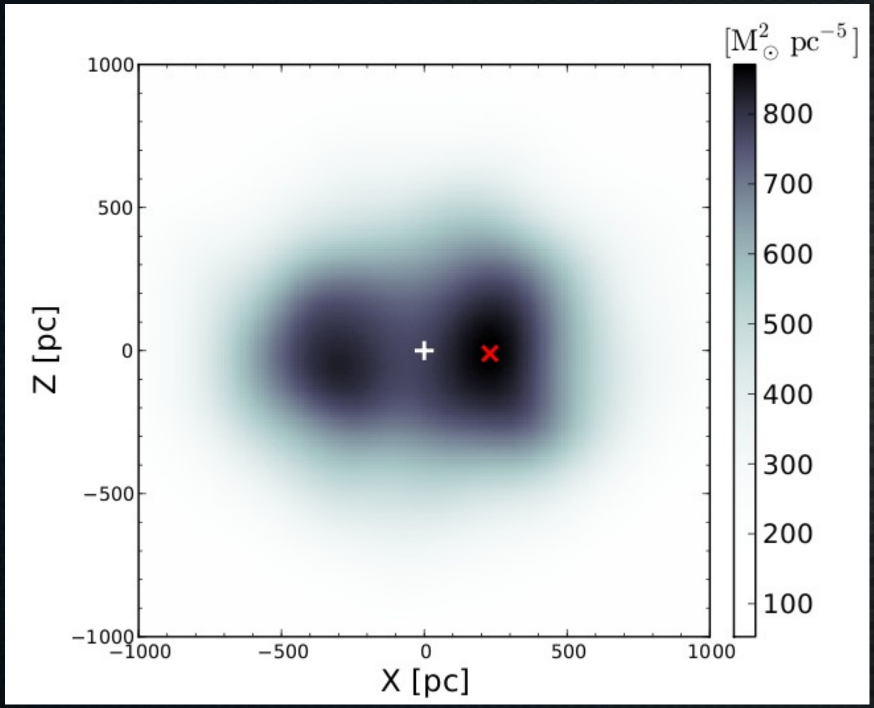


The angle in the disk plane to the offset shows periodic behavior.



DM annihilation implications?



At the resolution of the Eris simulation the contrast in DM annihilation surface brightness between the peak and the Galactic Center is only ~10-15%.

Such a low contrast is not compatible with a DM annihilation interpretation of the 130 GeV line.

HOWEVER: WE DO NOT RESOLVE THE OFFSET PEAK!
The contrast may increase with higher resolution...

Conclusions

- Ultra-high resolution DM simulations of Galactic structure predict enormous amounts of substructure, both in configuration space (subhalos) and in velocity space (streams, debris flow).
- This substructure has important consequences for astro-physical probes of DM, and **indirect (annihilation)** and **direct (nuclear scattering) detection** experiments.
- Cold and collisionless DM-only simulations by themselves are nearing the end of their usefulness.

- Baryonic physics is too important to neglect on small scales. Results are uncertain due to treatment of hydrodynamics and prescription of cooling, star formation, and especially feedback physics.
- Often even the sign of the effect (e.g. adiabatic contraction vs. cusp-to-core transformation) is unknown.
- Nevertheless, important progress is being made (e.g. Eris simulation), and are highlighting some important modification to expectations from DM-only simulations. Two examples:

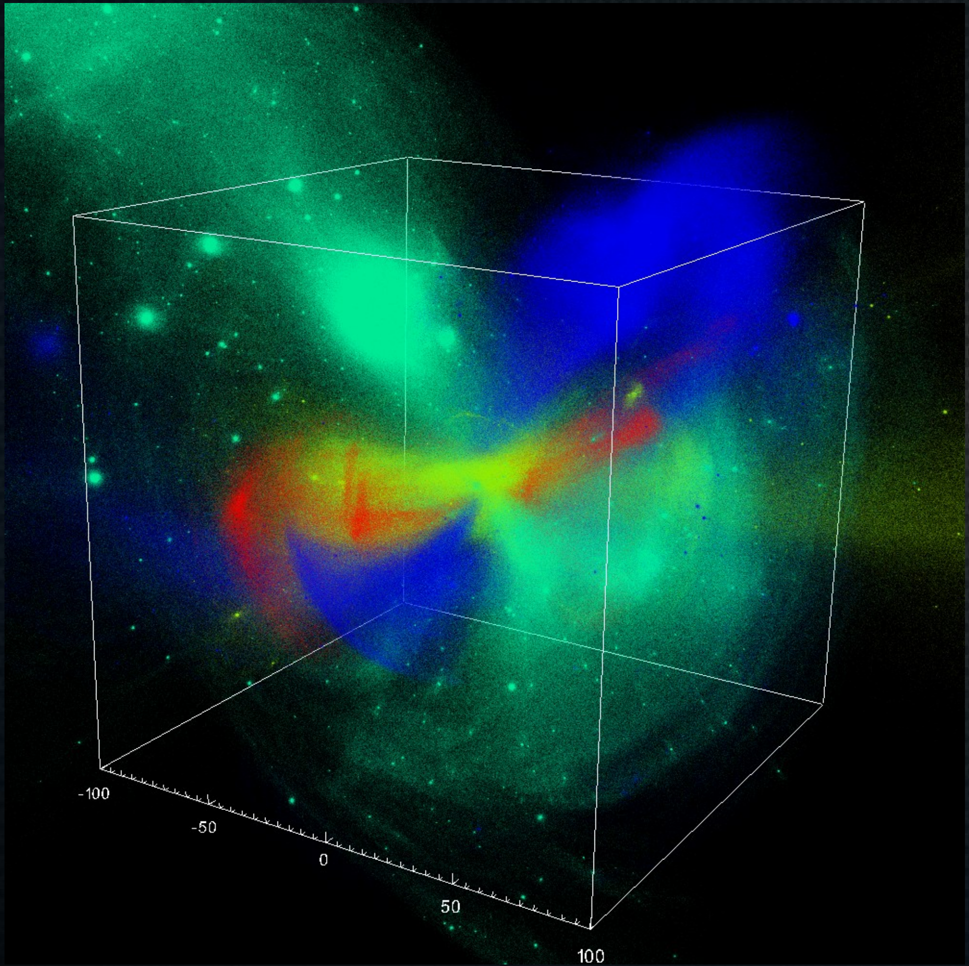
1) A Baryonic Solution to Too Big To Fail

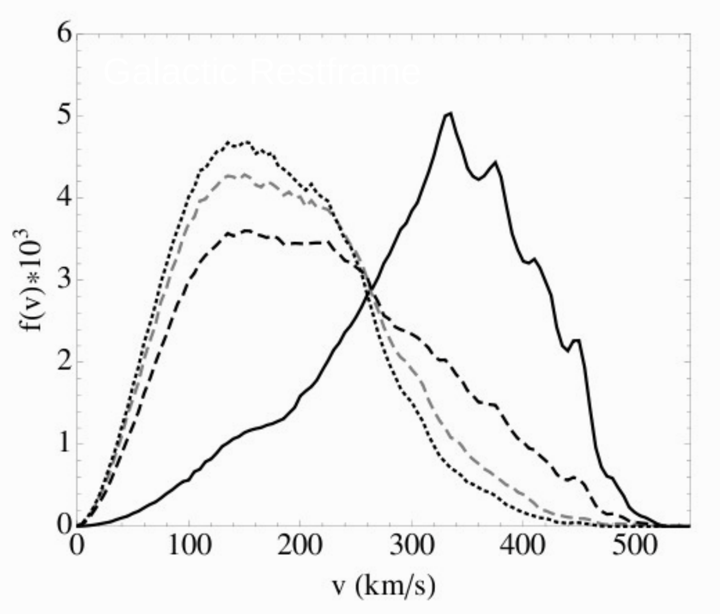
2) An Offset DM Density Peak at the Galactic Center

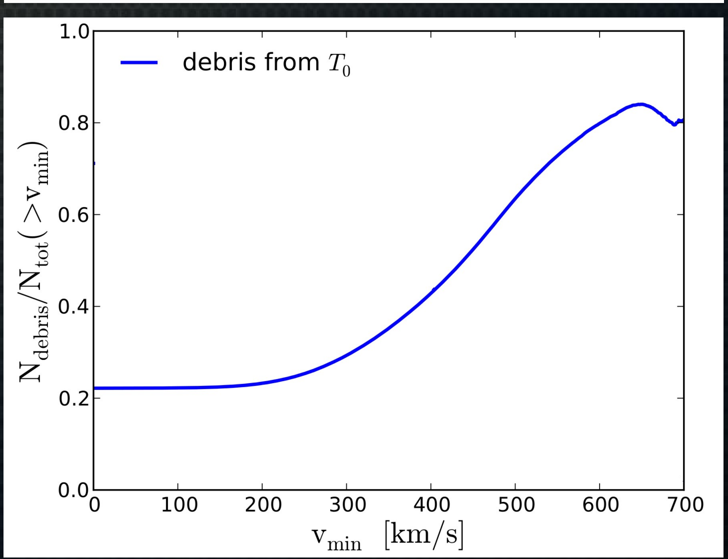
Extra Slides

Debris Flow

"Debris Flow" = Any material that was bound to a subhalo at z>0 and is no longer bound to it at z=0.







Kuhlen, Lisanti, & Spergel (2012)

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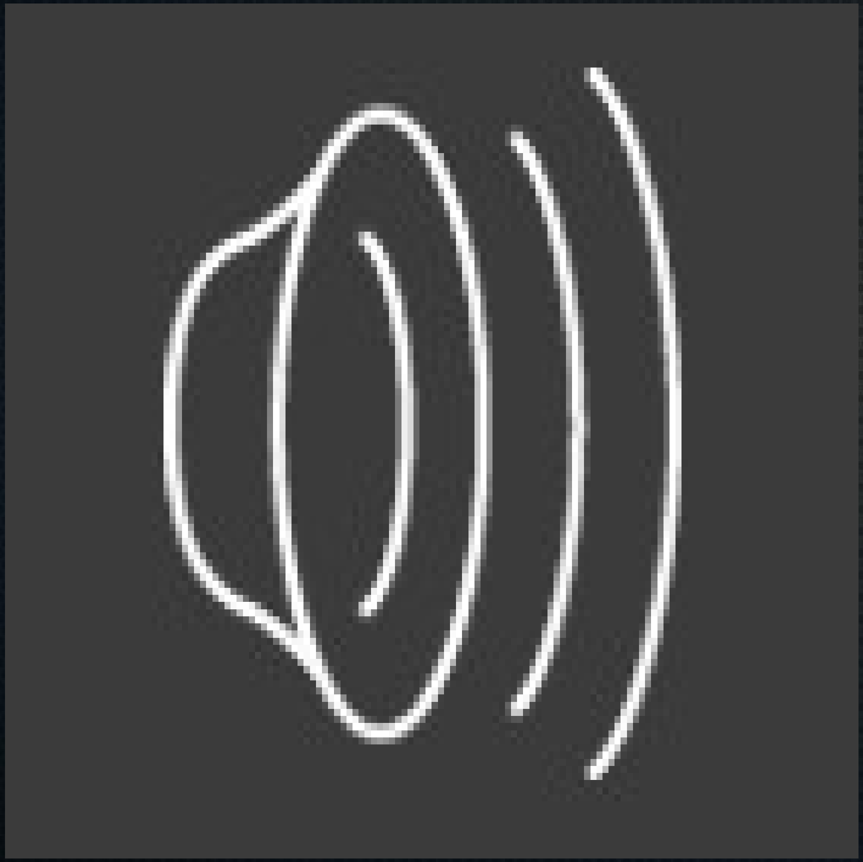
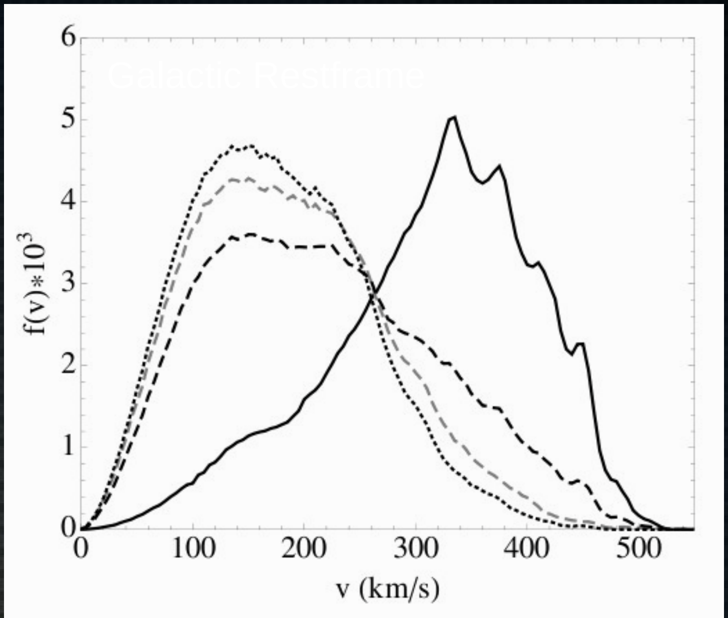
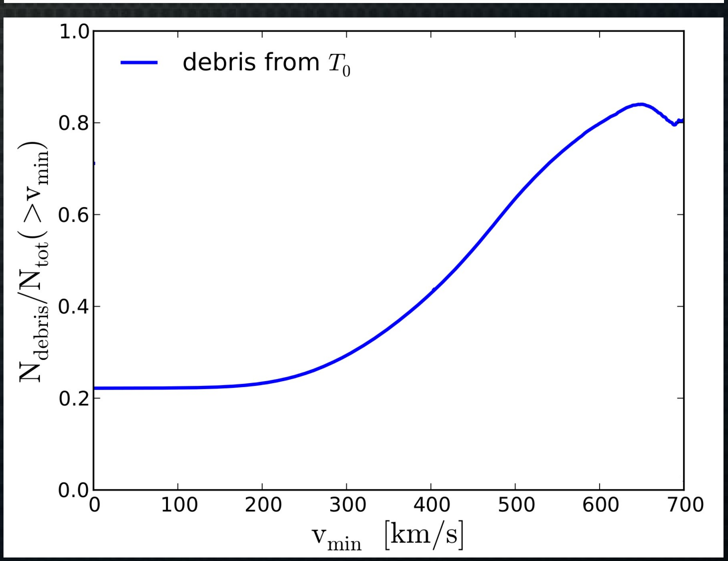
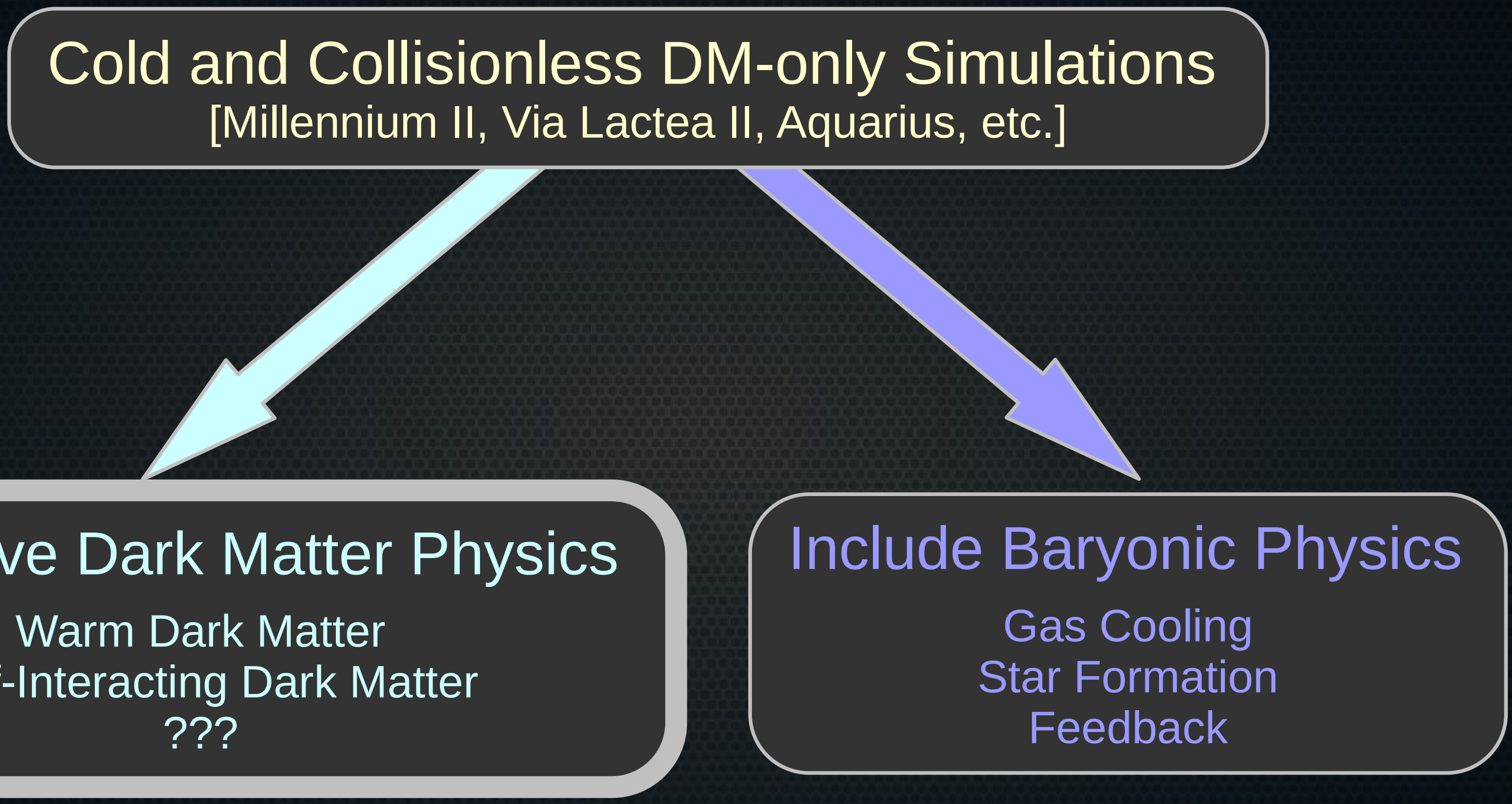






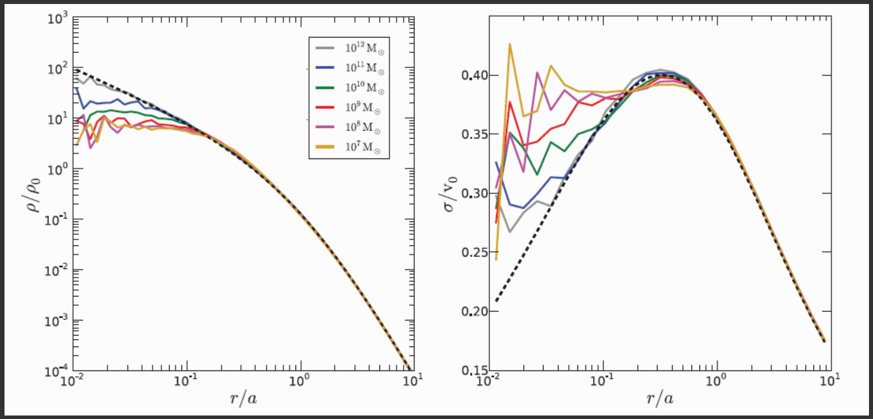
Kuhlen, Lisanti, & Spergel (2012)

Beyond Cold & Collisionless DM-only Simulations



Alternatives: Self-Interacting Dark Matter

Halos develop a density core.



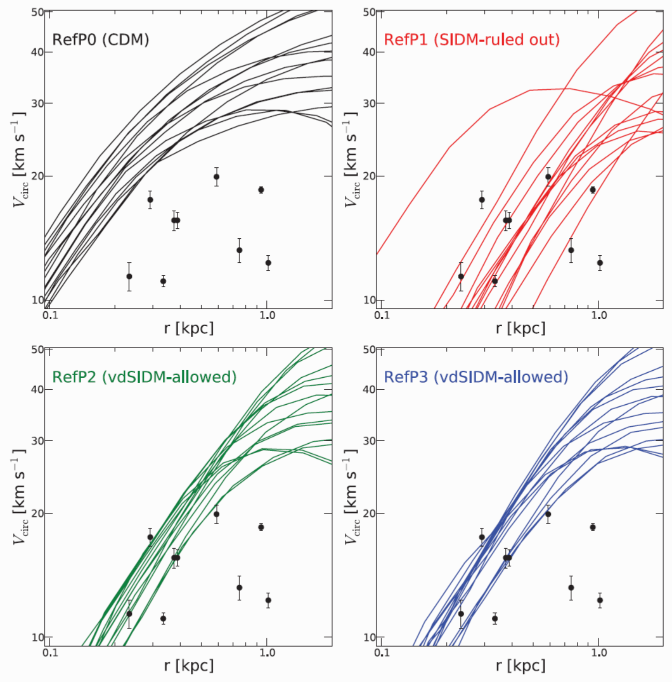
Vogelsberger, Zavala, & Loeb (2012)
See also Rocha, Peter, et al. (2012)

Velocity-dependent scattering cross section:

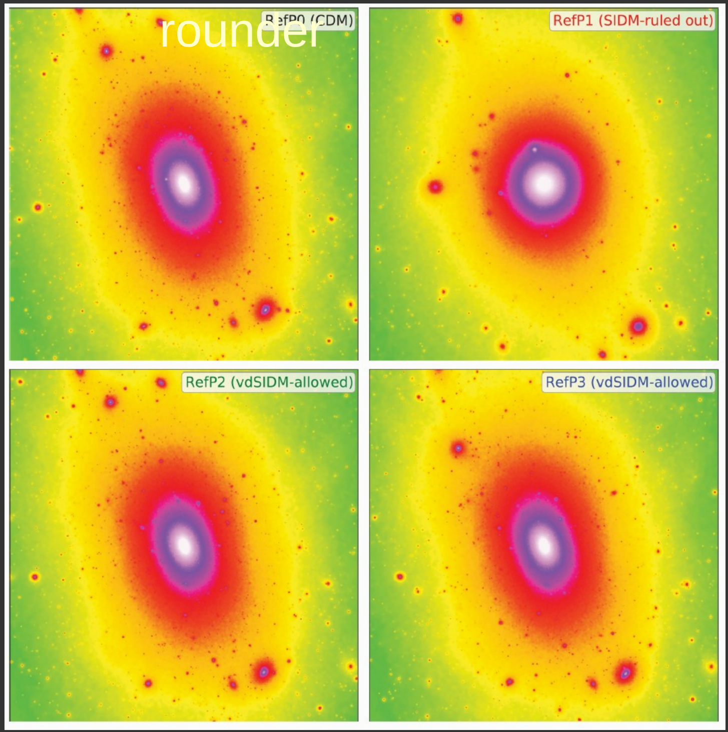
$$\frac{\sigma_T}{\sigma_T^{\max}} \approx \begin{cases} \frac{4\pi}{22.7}\beta^2 \ln(1+\beta^{-1}), & \beta < 0.1, \\ \frac{8\pi}{22.7}\beta^2 (1+1.5\beta^{1.65})^{-1}, & 0.1 < \beta < 10^3, \\ \frac{\pi}{22.7}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2, & \beta > 10^3, \end{cases}$$

Feng, Kaplinghat, & Yu (2010), Finkbeiner et al. (2011), Loeb & Weiner (2011)

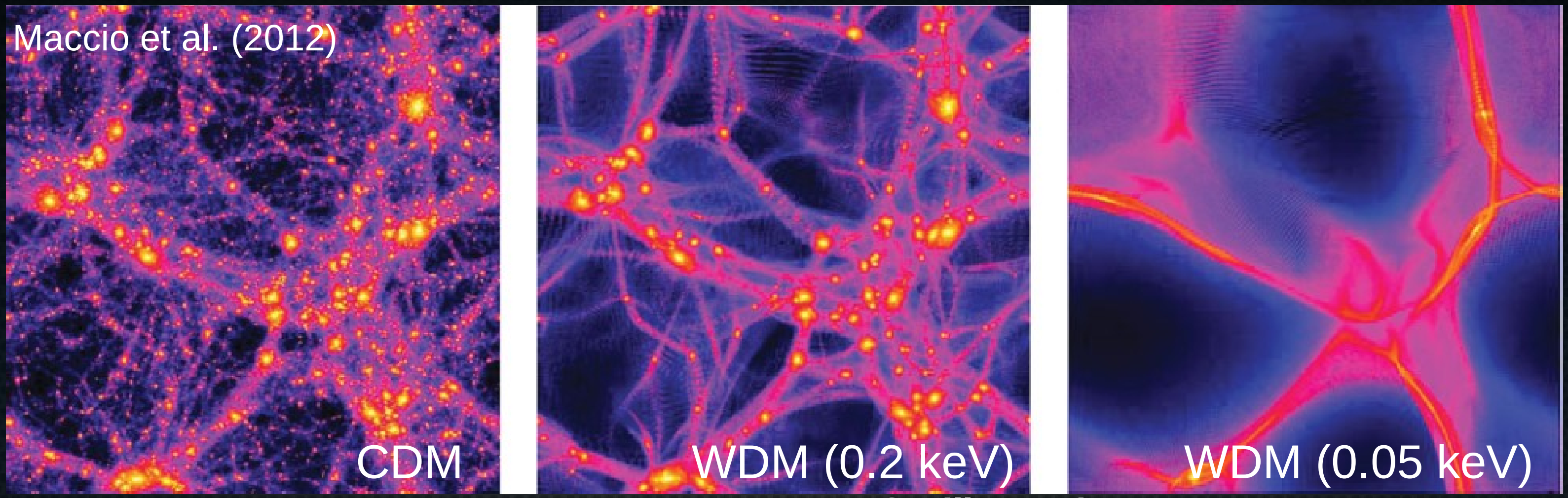
Reduced central density.



Makes halos rounder

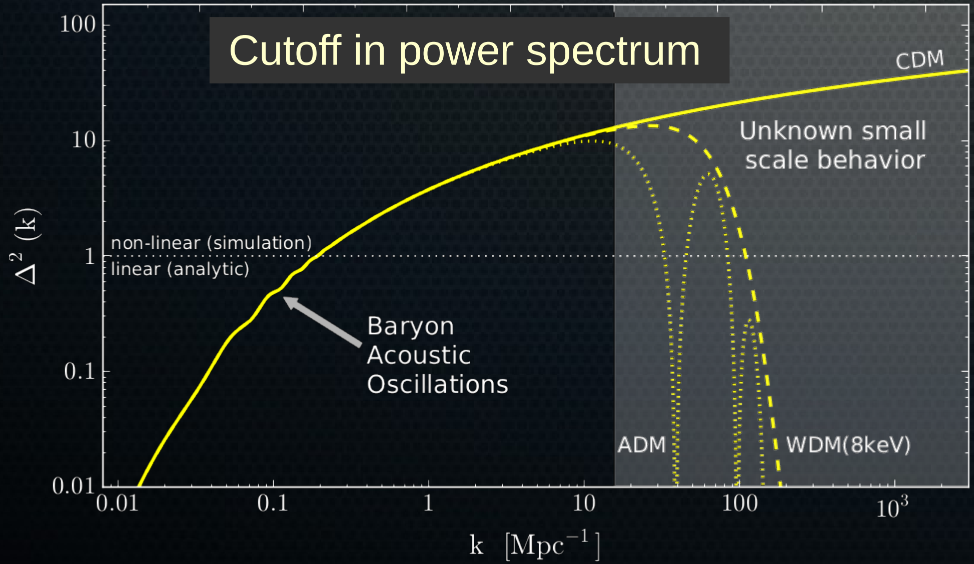


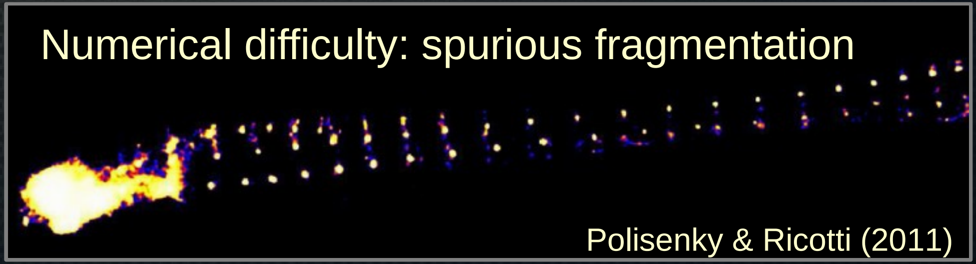
Alternatives: Warm Dark Matter



Just for illustration purposes!

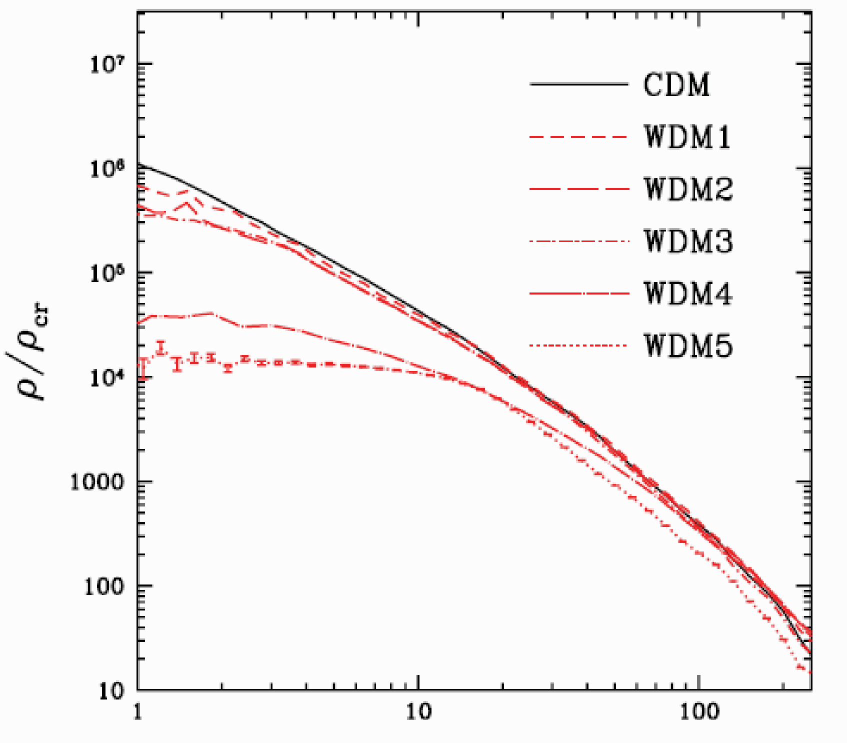
Observational Limits from Ly-α forest: $m_{WDM} > 2 - 4$ keV.
(Viel et al. 2006, 2008; Abazajian 2006; Seljak et al. 2006)



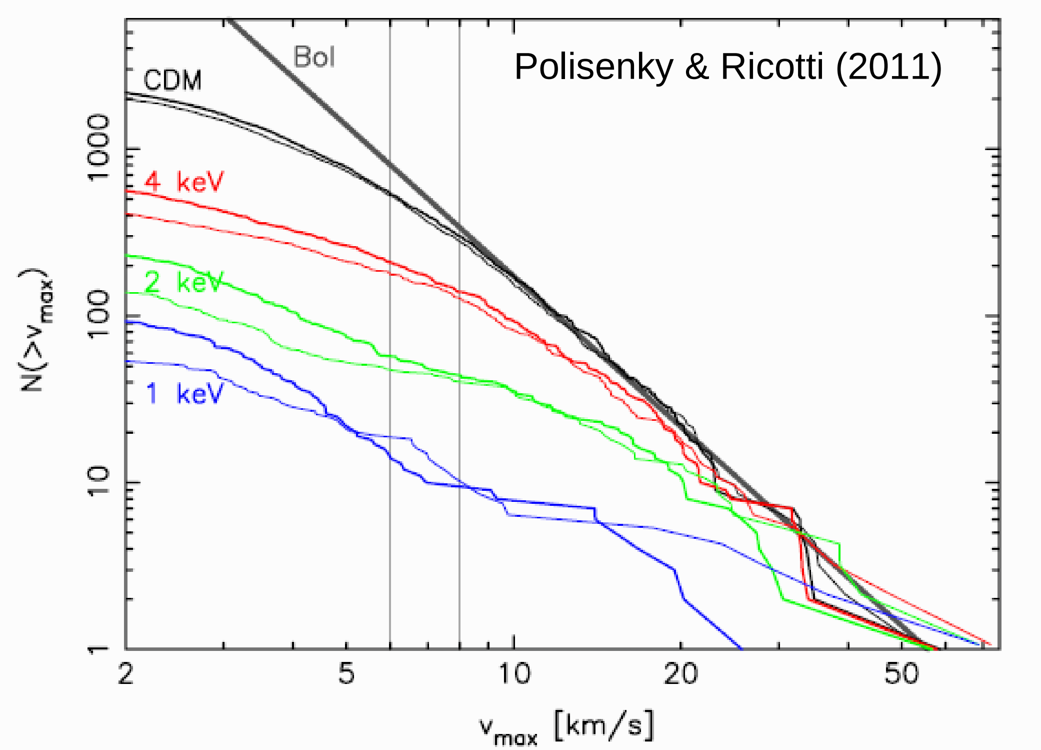


See also: Bode et al. (2001), Gao & Theuns (2007), Lovell et al. (2011), Maccio et al (2012)etc.

Alternatives: Warm Dark Matter



Maccio et al. (2012)



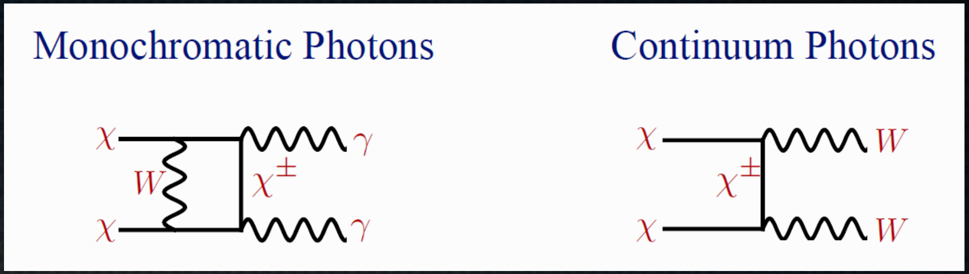
Catch-22: either you get cores, but not enough subhalos, or you can match the ultra-faint dwarfs, but then you don't get big enough cores.

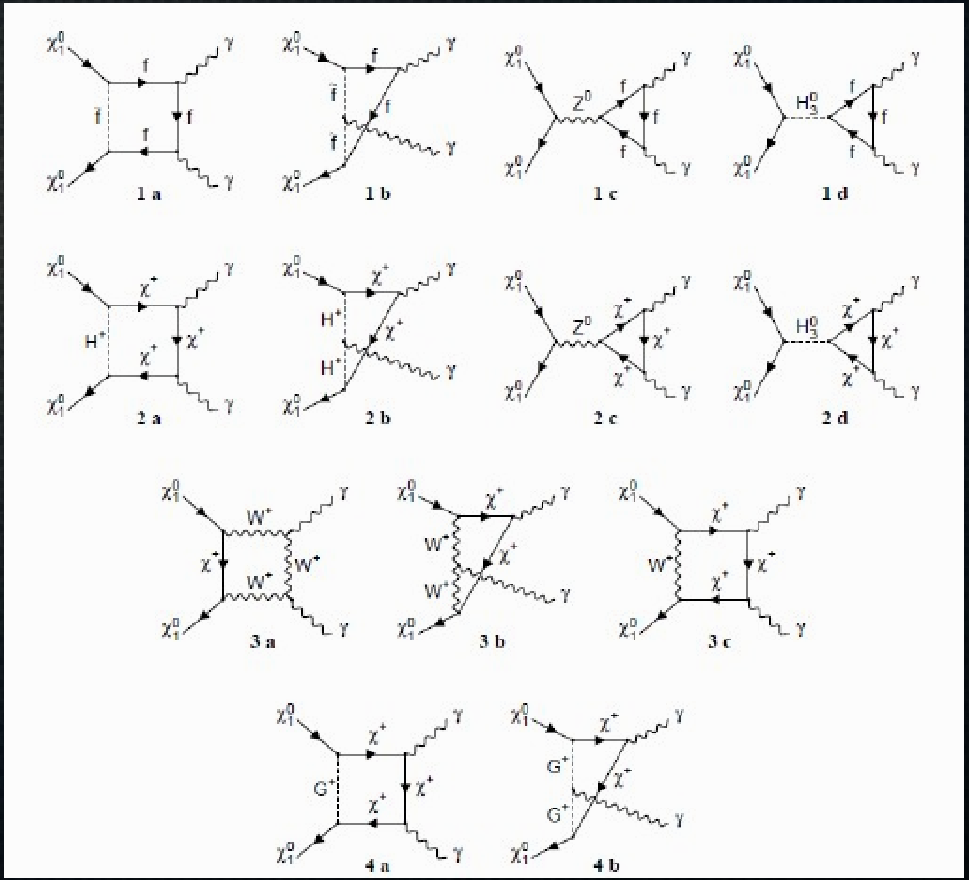
Villaescusa-Navarro & Dalal (2011), Maccio et al. (2012)

Is this DM annihilation?

DM annihilation?

- 2-body annihilation: $\chi\chi \rightarrow \gamma\gamma,\ \gamma Z,\ \gamma h$
- Normally “loop suppressed“ ($10^{-2} - 10^{-4}$) compared to continuum radiation.
- But models with enhanced lines exist, e.g.: Singlet DM (Profumo et al. 2010) “Higgs in Space“ (Jackson et al. 2010)





Bergström & Ullio 1997

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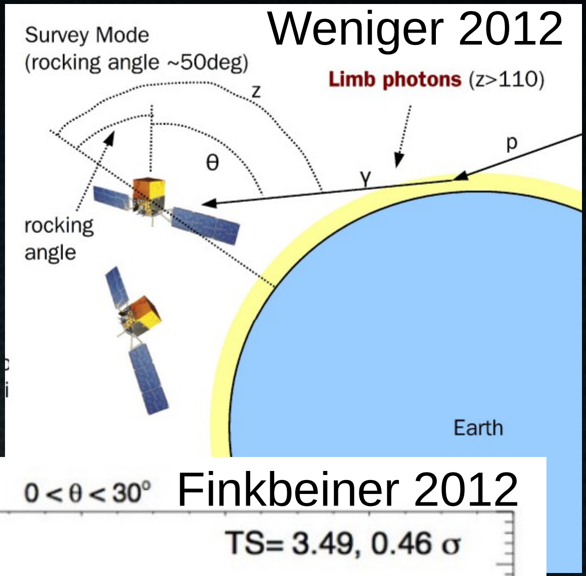
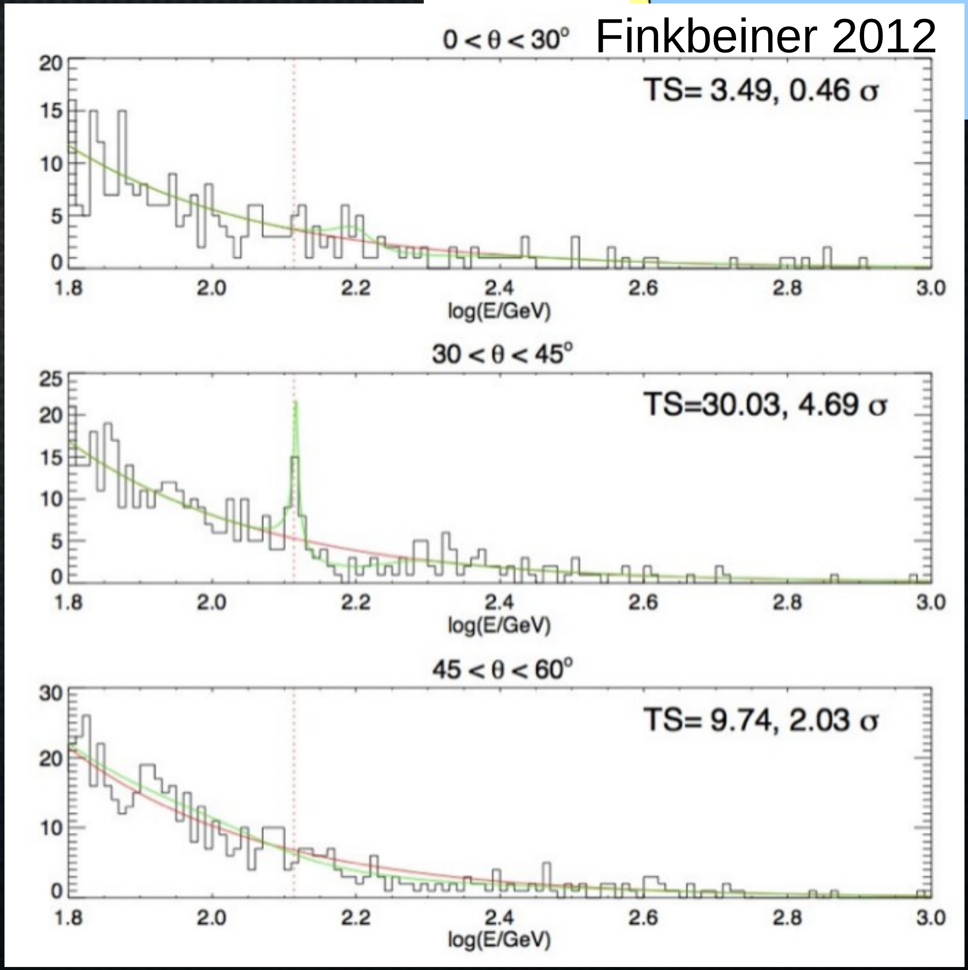
Instrument systematics?

- Earth limb photons of intermediate incidence angle show a similar line...





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Astrophysical explanations?

- Broken power-law mimics line?
  (Profumo & Linden 2012)
- Inverse Compton in the Klein-Nishina regime with ~130 GeV mono-chromatic electrons from multiple pulsars?
  (Aharonian et al. 2012)

Cold ultrarelativistic pulsar winds as potential sources of galactic gamma-ray lines above 100 GeV

Felix Aharonian[1,2], Dmitry Khangulyan[3], Denis Malyshev[4]

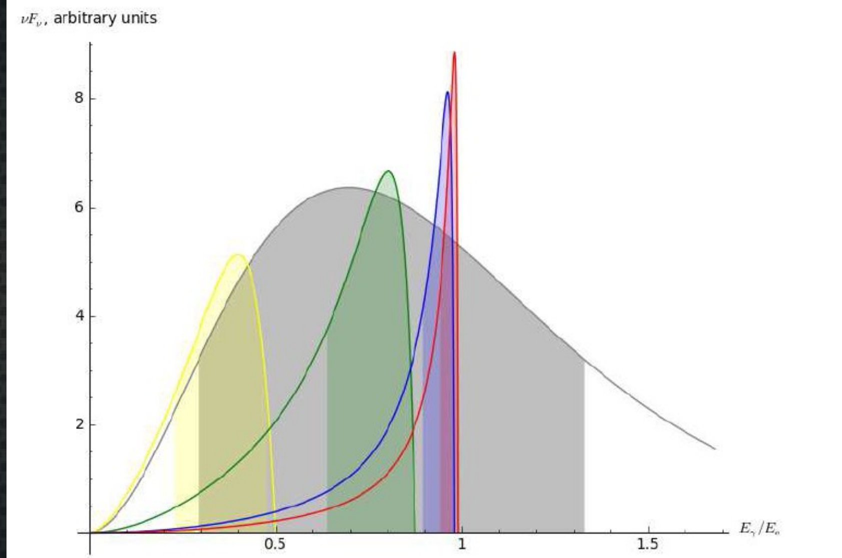

Fig. 1. *Colour*: energy spectra of the inverse Compton radiation of mono-energetic electrons upscattering isotropic target photons for 4 different values of the parameter b: 1, 7, 50 and 100. The energy of gamma-rays is in units of the electron energy. *Grey*: the gamma-ray spectrum produced by electrons with relativistic Maxwellian distribution; in this case the photon energies are in units of 4Θ, where Θ is the "temperature" of Maxwellian distribution.